Energy and Emissions Forecast for Vermont: *Mitigation Pathways*

Stockholm Environment Institute

16 November 2021

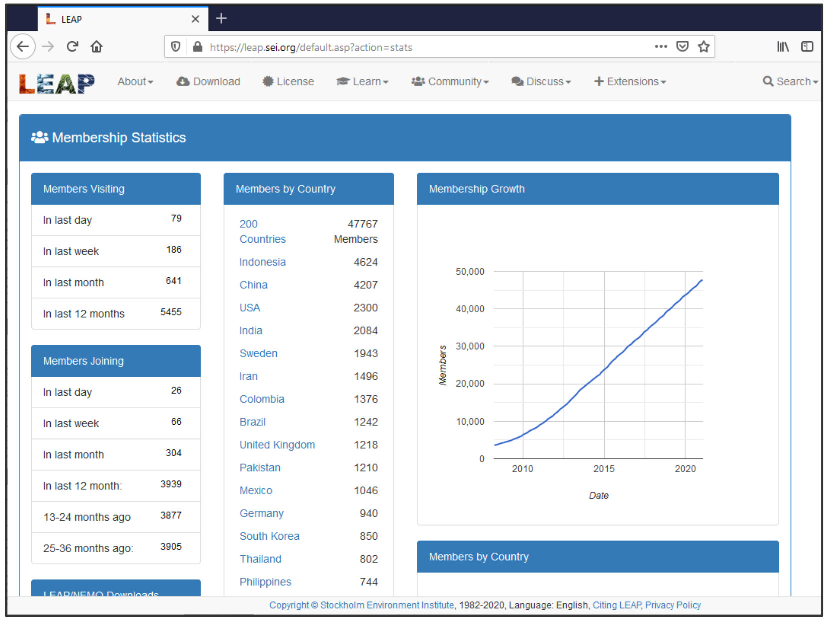
Generated using Vermont LEAP model version 1.83

Modeling Tool

- **Low Emissions Analysis Platform (LEAP)**
  - A software tool for **quantitative modeling** of:
    - Energy systems
    - Pollutant emissions from energy and non-energy sources
    - Health impacts
    - Sustainable development indicators
    - Costs and benefits
    - Related externalities
  - Developed by SEI
  - Distinguished by **data and methodological flexibility, graphical user interface**, built-in **accounting features** (energy, emissions, costs, natural resources)
  - **Thousands of users** across 190+ countries

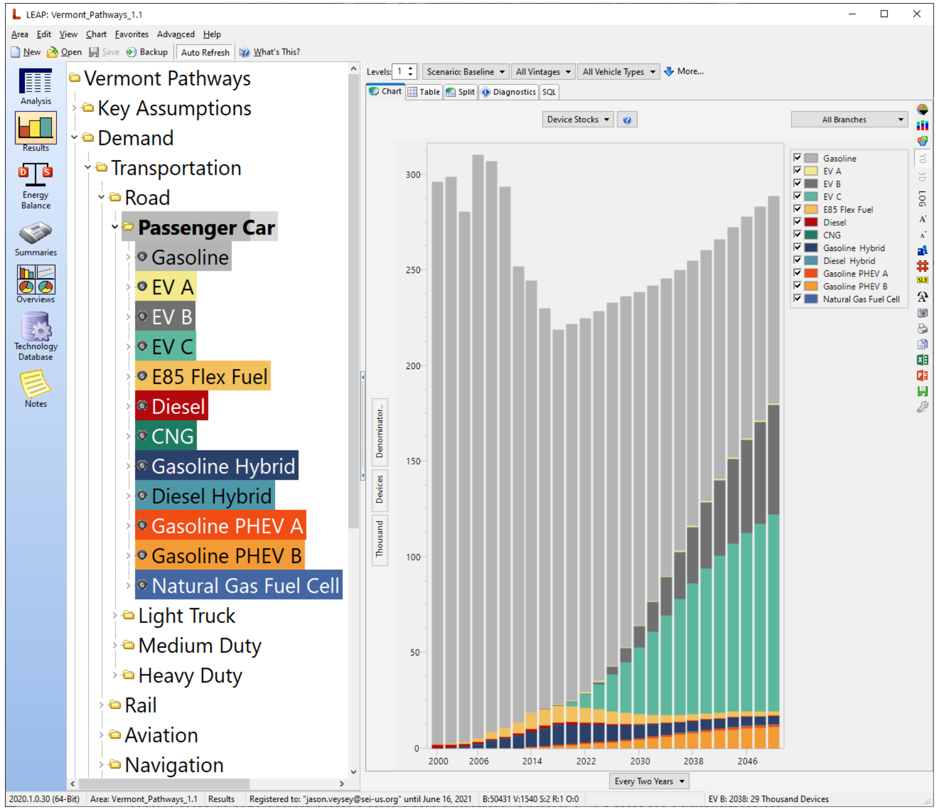
LEAP

https://leap.sei.org



Model Scope and Methods

- Modeling period: **2015-2050**, with scenario(s) beginning in 2020
- Model covers **all energy demand, energy supply**, and **GHG emissions in Vermont** (all sectors including emissions from **energy and non-energy** sources)
- GHG emissions converted to **CO_2-equivalent** using 100-year global warming potentials from Intergovernmental Panel on Climate Change's **Fourth Assessment Report**



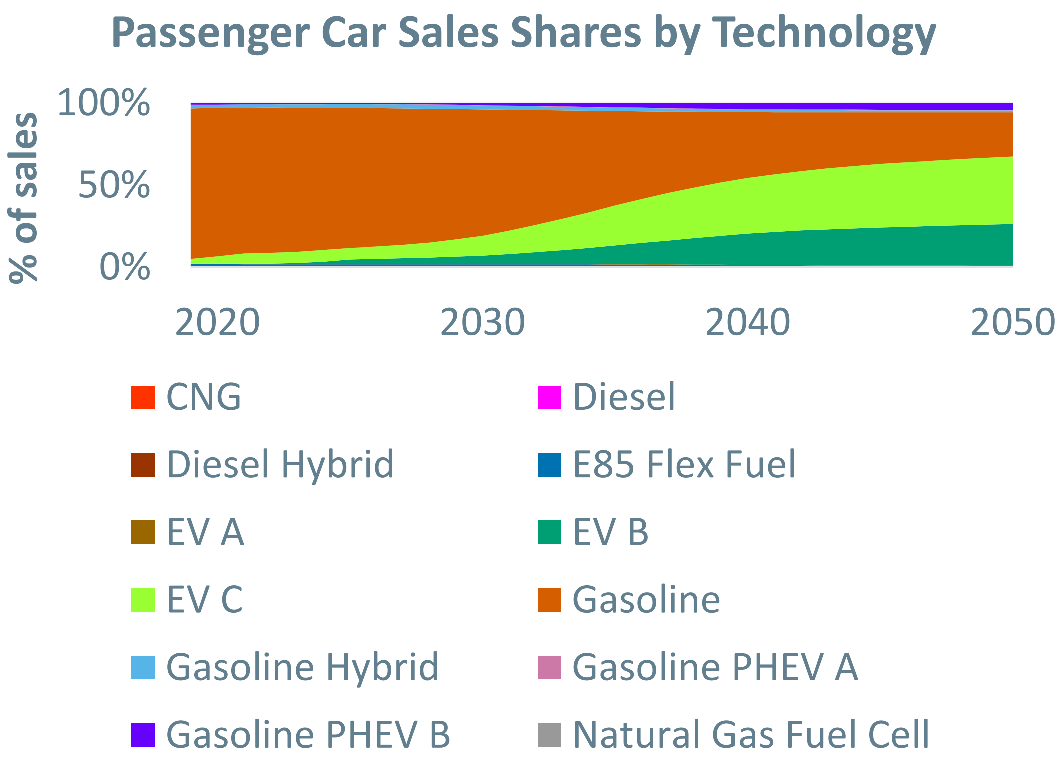
Business-as-Usual Data Sources and Results

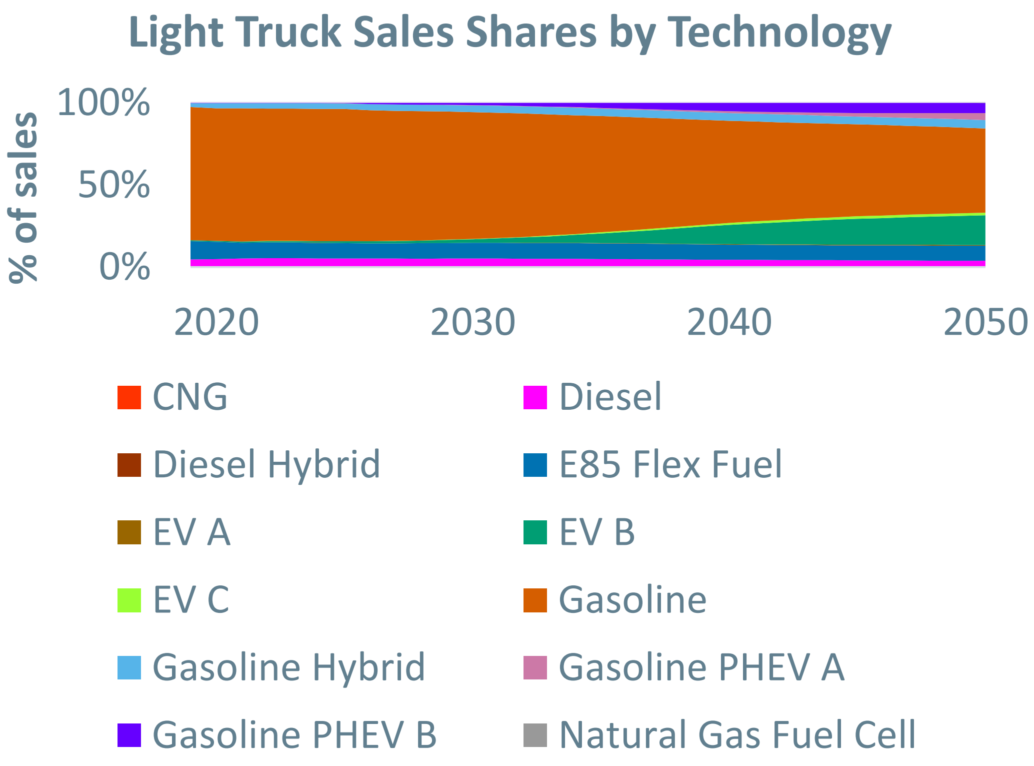
On-Road Transportation

What's Included?

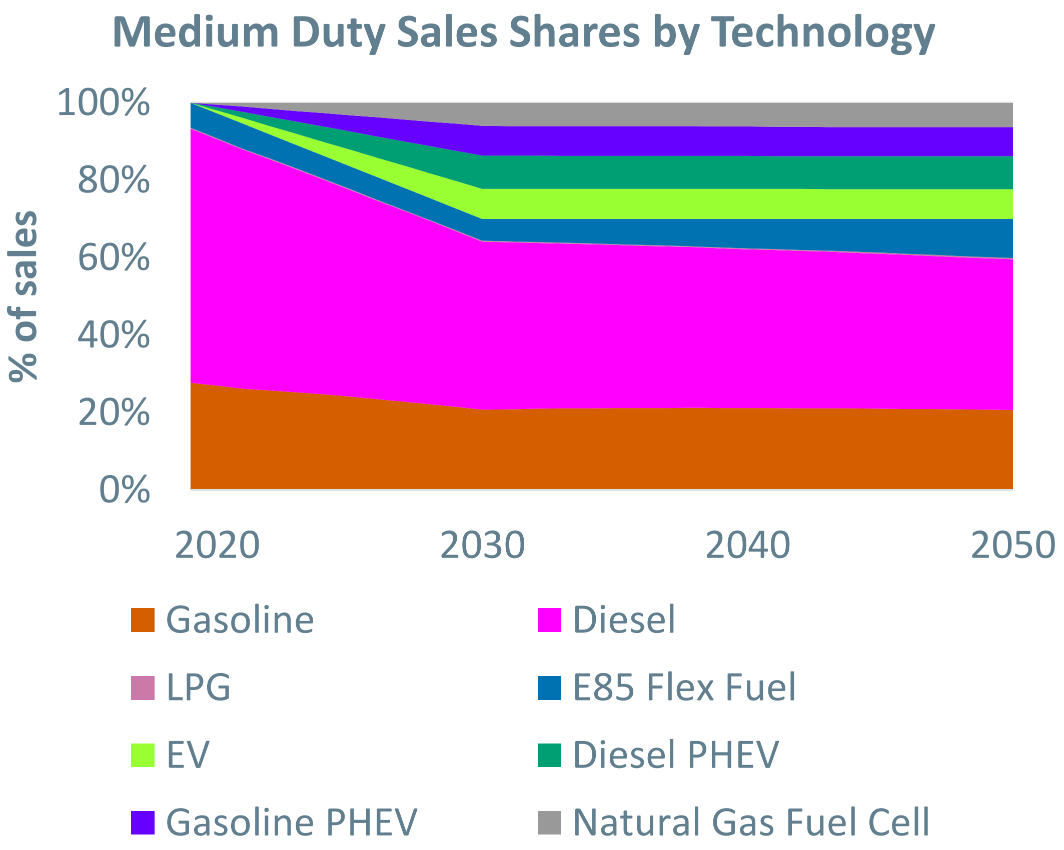
- Registrations of publicly and privately owned road vehicles from VDMV
- Historical vehicle registrations from UVM TRC (Dowds) and FHWA
- Historical and forecasted VMT from UVM TRC (Sullivan)
- Fuel economy and mileage over vehicle lifetime from VISION 2020 model, including ethanol and biodiesel blends
- EV sales from VELCO (light-duty) and multi-state MOU (medium- and heavy-duty)
- Other vehicle sales forecasts aligned with AEO 2020
- GHG emissions from EPA's SIT and GREET

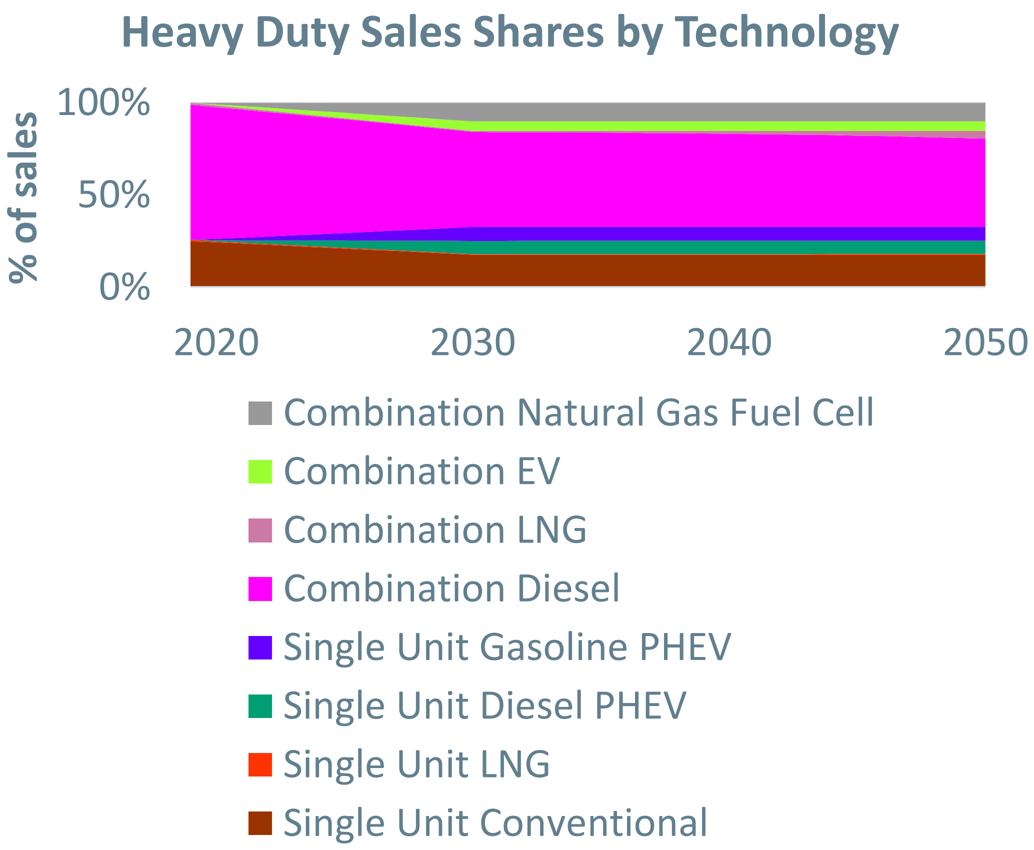
On-Road Transportation: Business-as-Usual Sales



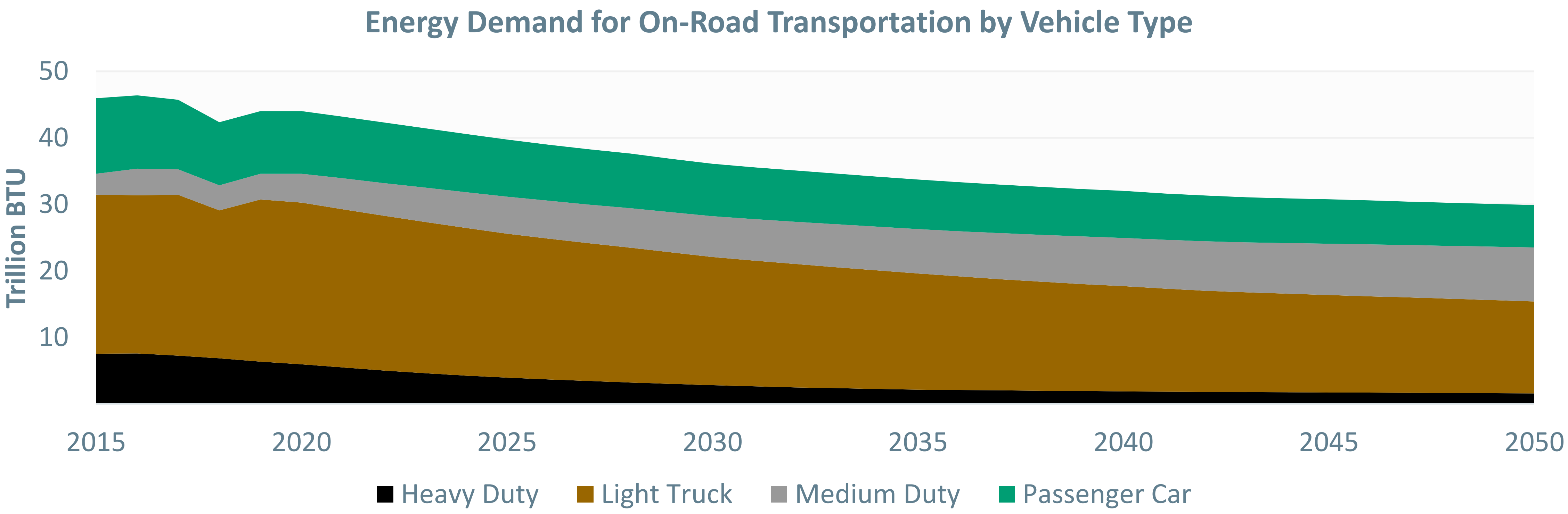


On-Road Transportation: Business-as-Usual Sales

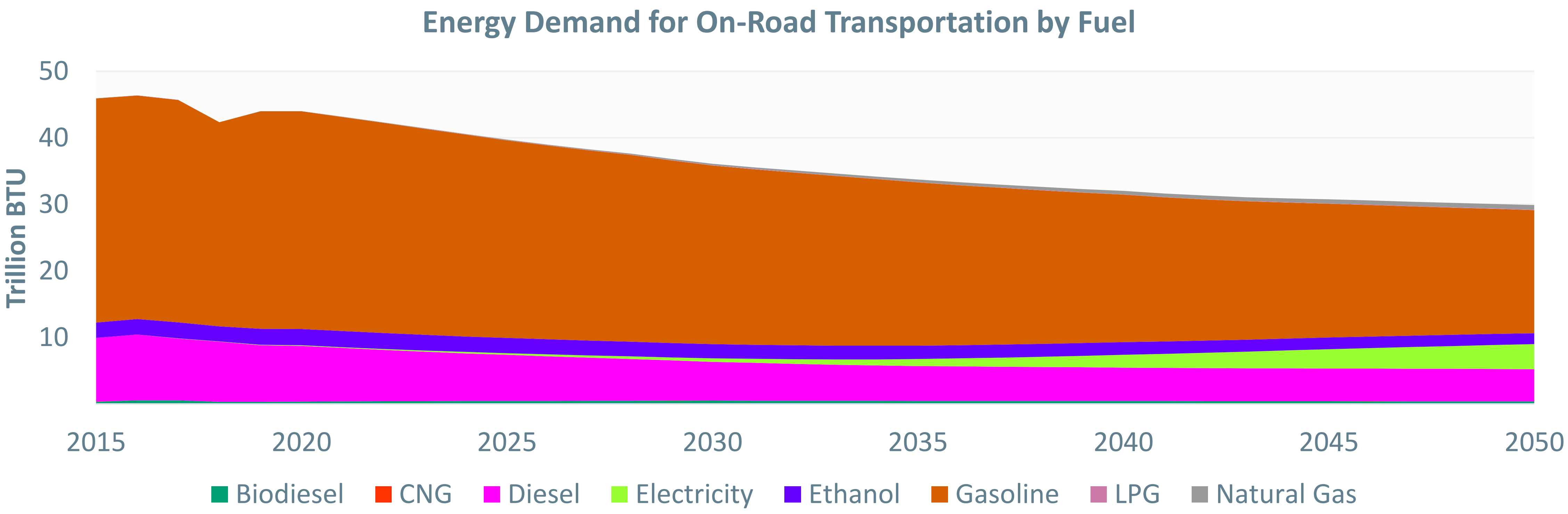




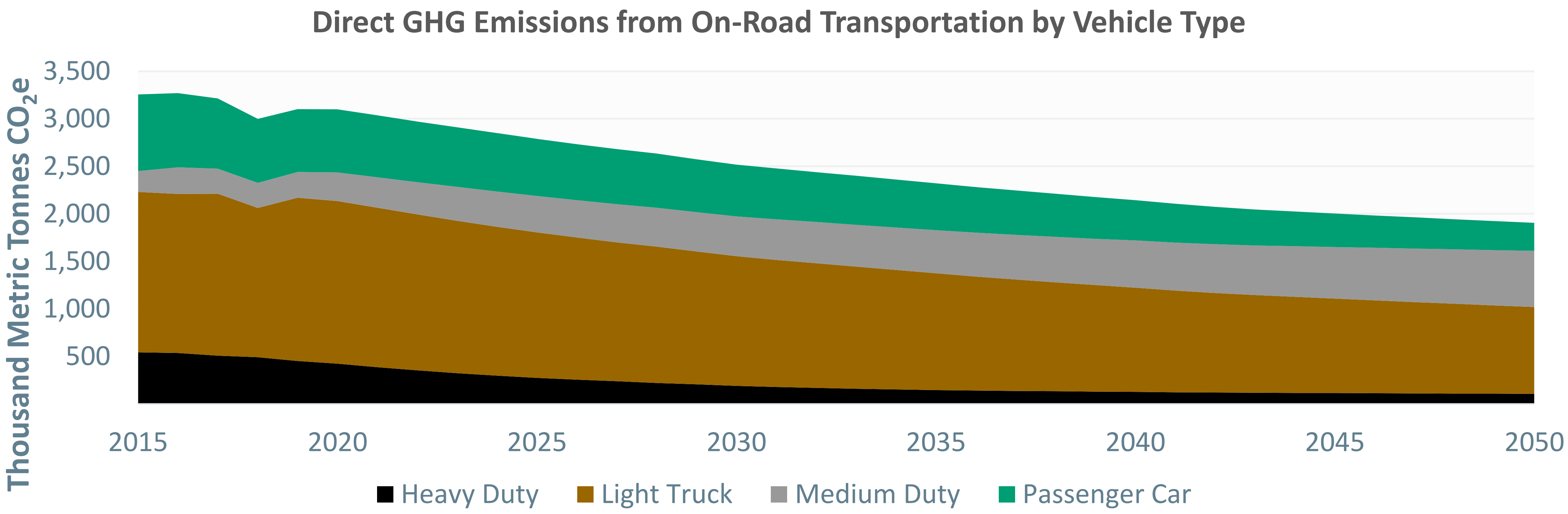
On-Road Transportation: Business-as-Usual Results



On-Road Transportation: Business-as-Usual Results



On-Road Transportation: Business-as-Usual Results

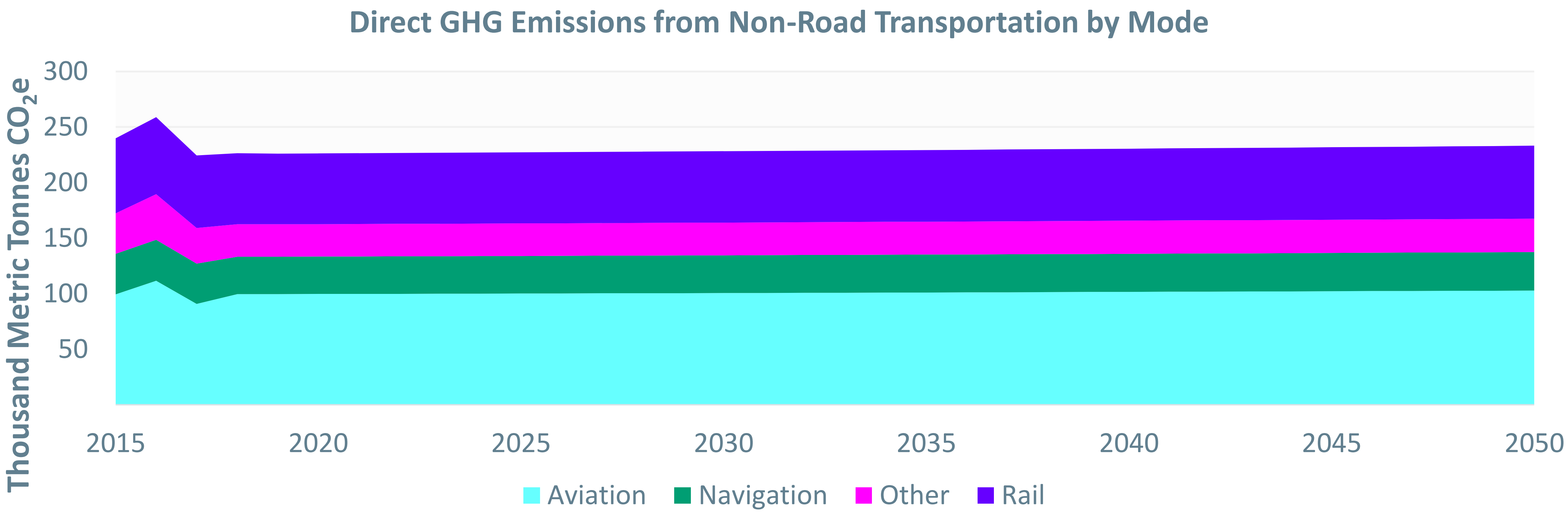


Non-Road Transportation

What's Included?

- Historical and forecasted rail, aviation, navigation, "other" fuel shares from AEO 2020
- Total energy consumption per capita derived from SEDS, and population forecasts from VT DOH and UVM TRC
- GHG Emissions from EPA's SIT

Non-Road Transportation: Business-as-Usual Results

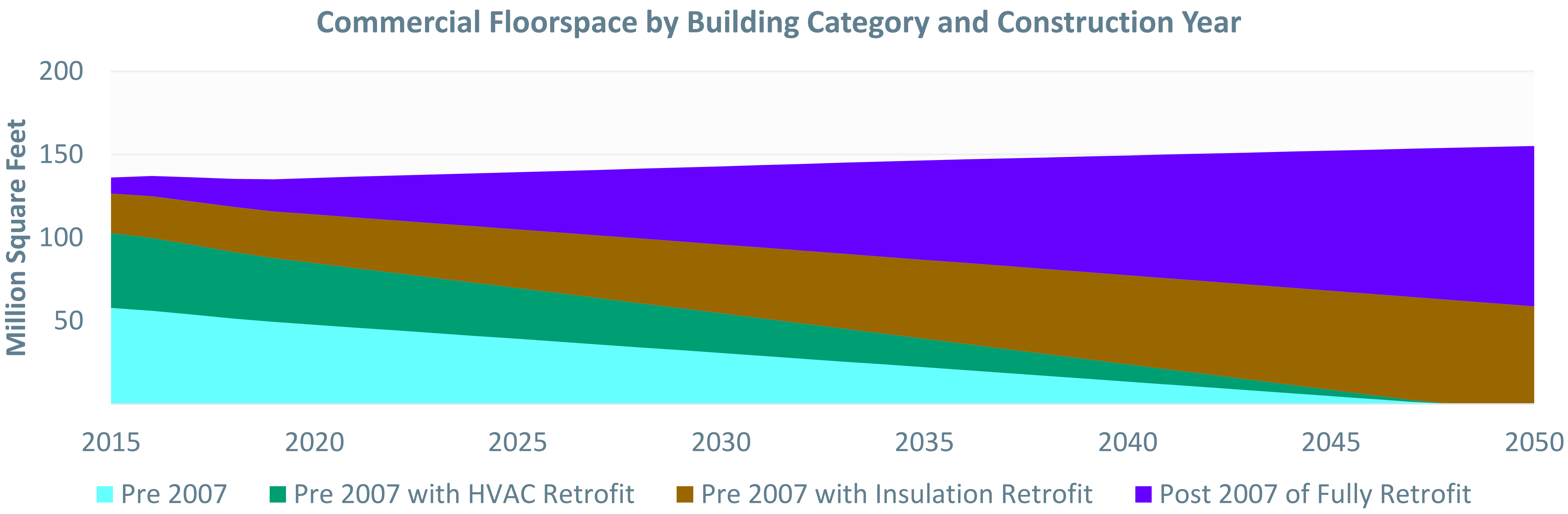


Commercial Buildings

What's Included?

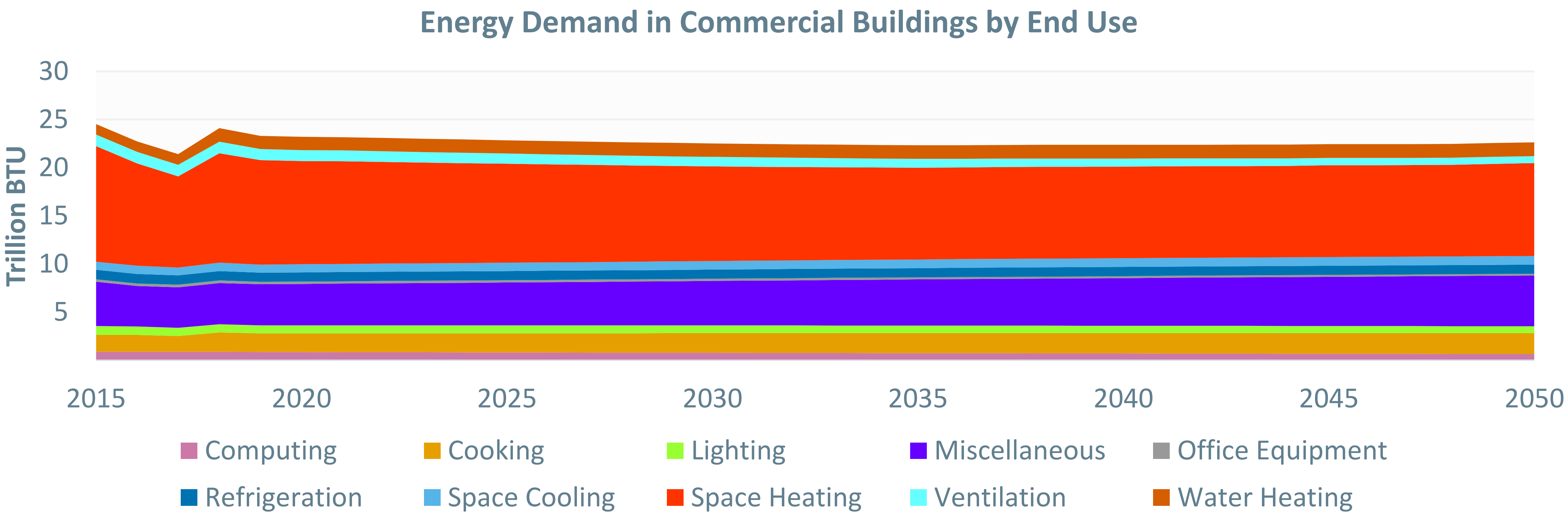
- Based on EIA CBECS
  - Floorspace for "pre-2007" buildings without retrofits, with HVAC retrofit, with insulation retrofits, "post-2007" buildings
  - Within each, penetration of different building technologies and energy use per square foot
  - Floorspace projections from AEO 2020 for New England, prorated for Vermont GDP from US BEA
- Adjustments to technology shares within space heating, lighting, water heating from PSD/Cadmus
- Estimated annual heat pump additions from VELCO/Itron
- Energy efficiency program thermal fuel savings and declining electricity use per square foot from EVT, total natural gas efficiency from Vermont PUC
- GHG emissions from EPA's SIT

Commercial Buildings: Business-as-Usual Assumptions

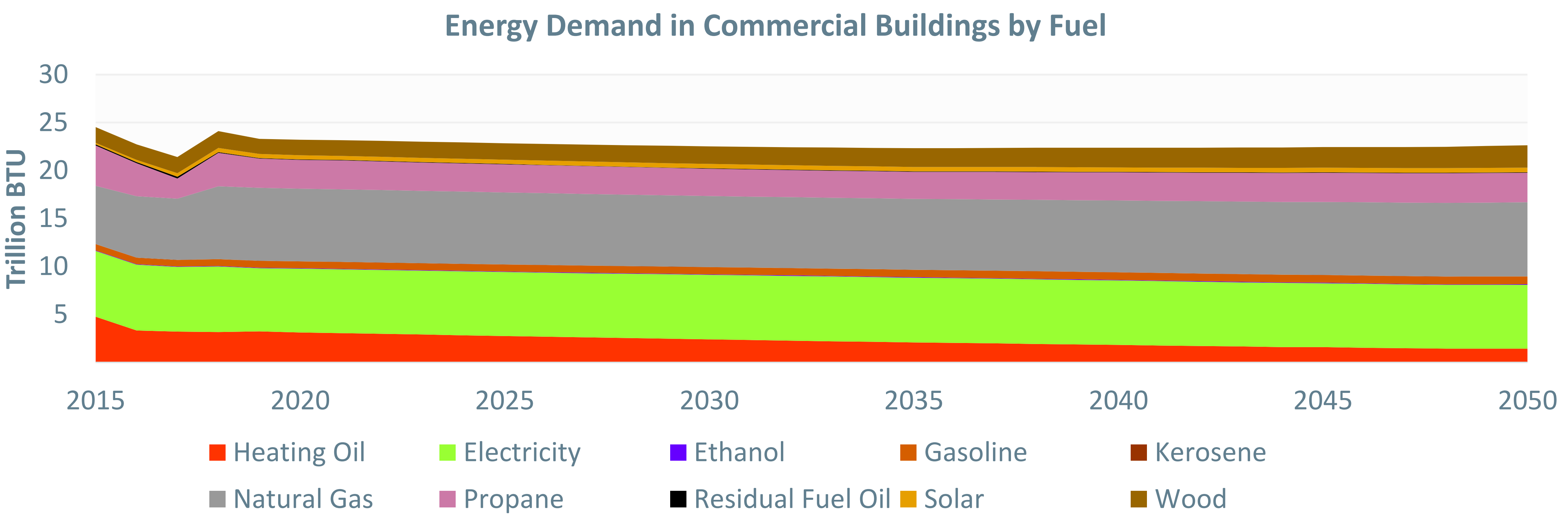


* Building category labels refer to construction year (ex. “Pre 2007” are buildings constructed before 2007).

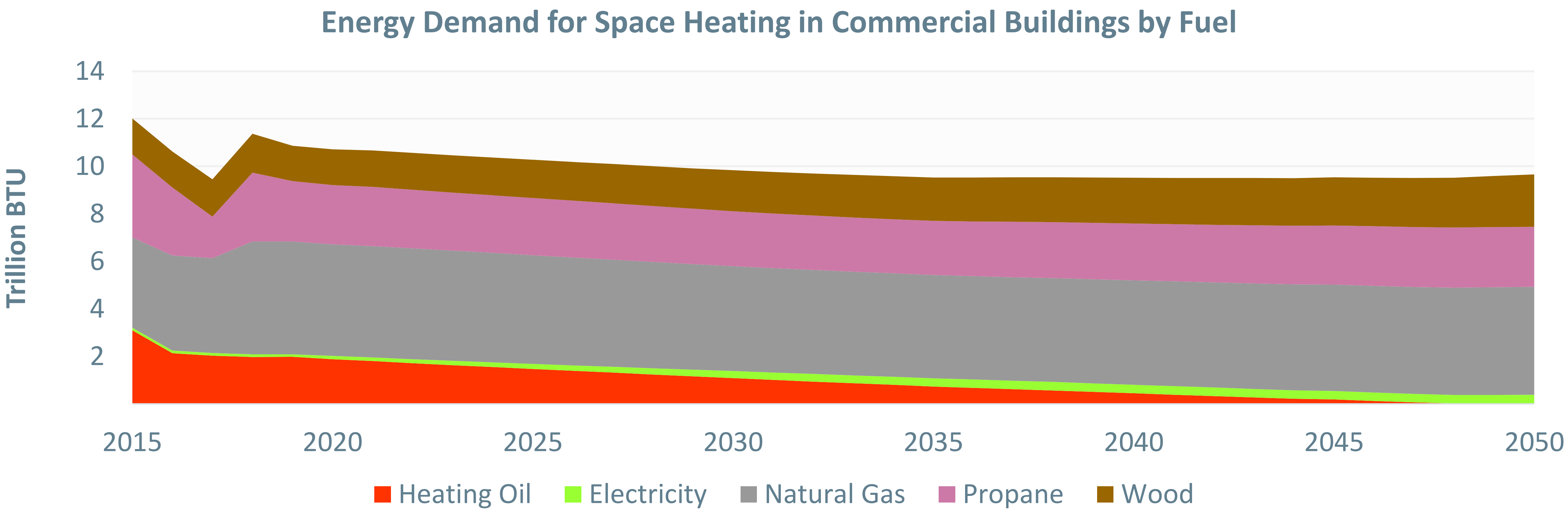
Commercial Buildings: Business-as-Usual Results



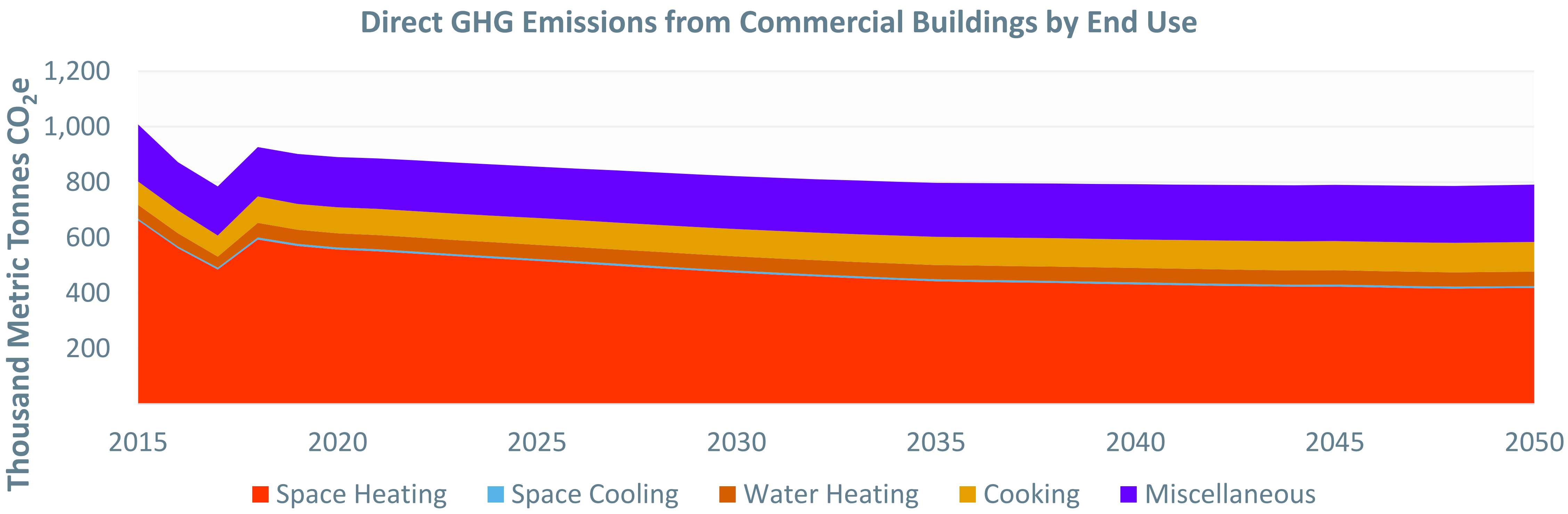
Commercial Buildings: Business-as-Usual Results



Commercial Buildings: Business-as-Usual Results



Commercial Buildings: Business-as-Usual Results



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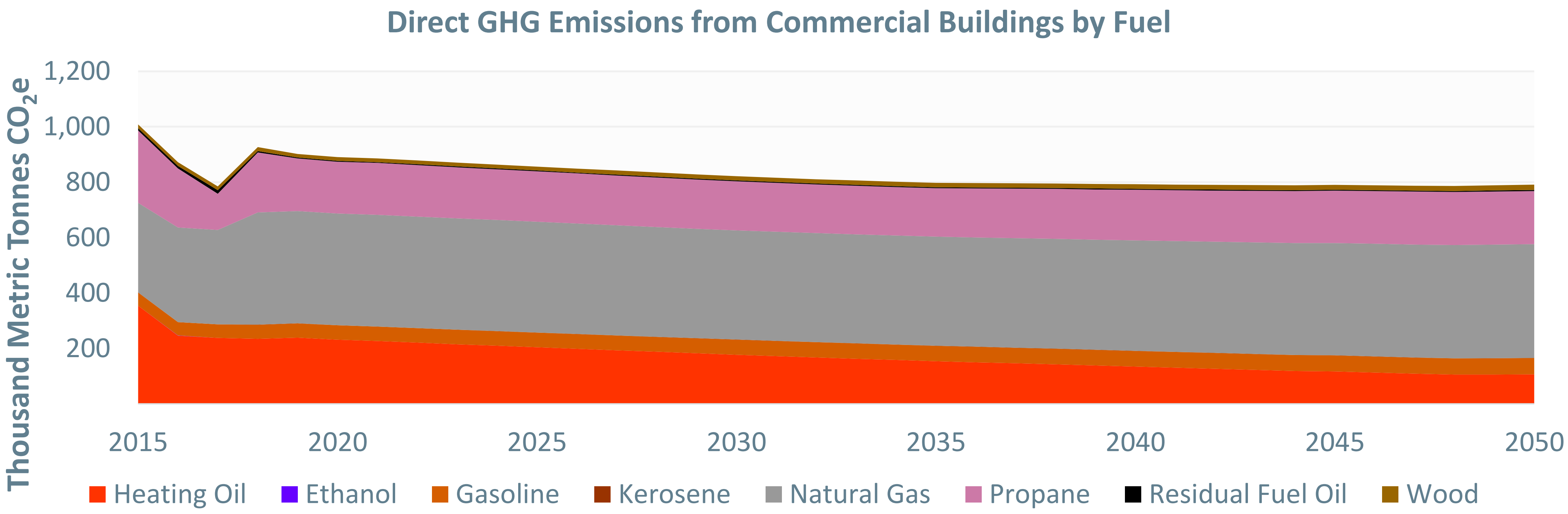


Residential Buildings

What's Included?

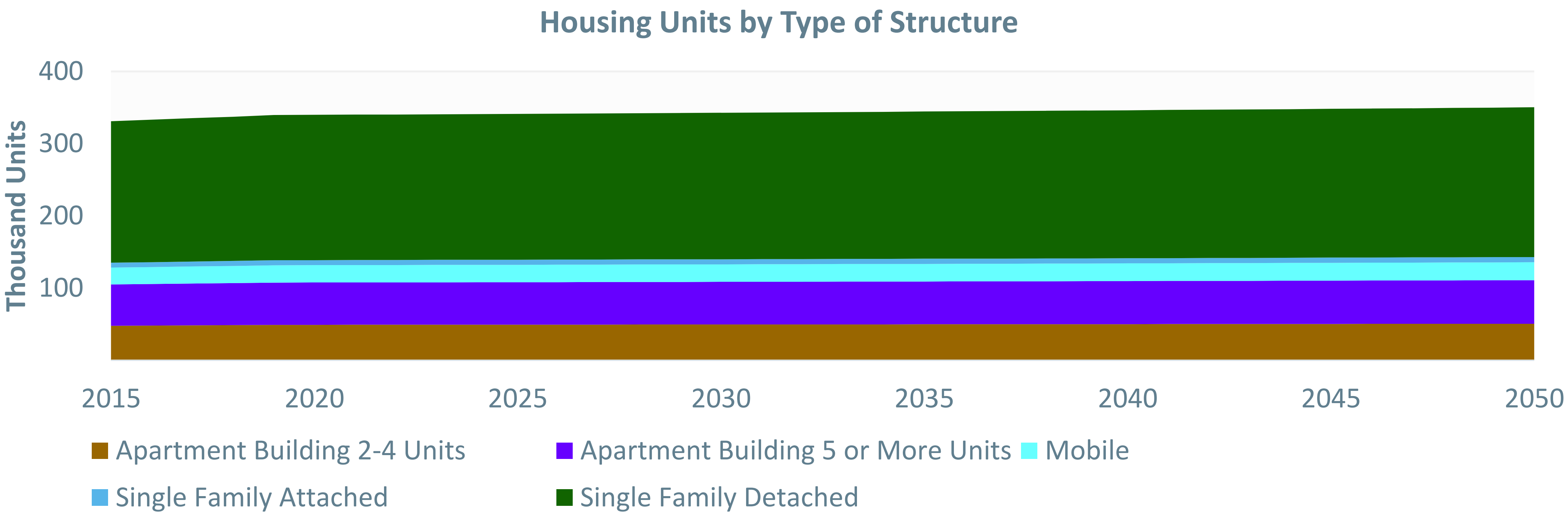
- Based on EIA RECS
  - Includes shares of housing units in urban vs. rural areas, by housing type and tenure, having different energy end uses and technologies
  - Technology and end use penetrations from VT Residential Market Assessment and RECS
  - Equipment efficiencies for non-wood fuels from RECS and VT Residential Market Assessment
  - Total housing units from Census Bureau, population forecast harmonized with UVM TRC
- VT Residential Fuel Assessment: total wood and pellet consumption in Vermont
- NESCAUM: wood and pellet stove combustion efficiencies
- VT Residential Market Assessment: technology penetration in new housing units

Residential Buildings (continued)

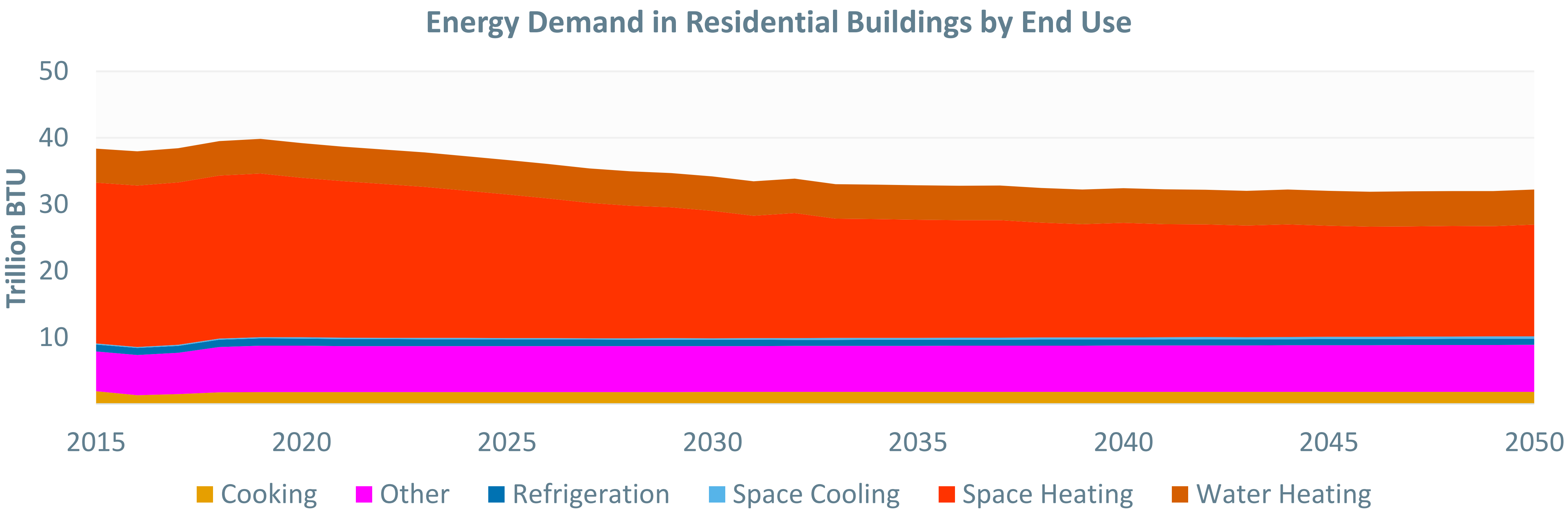
What's Included?

- Projected energy efficiency program savings by end use from EVEE
- Projected building shell retrofits (weatherization) from EVR and VGS, with building shell improvements in new construction from PSD/EVEE
- Changes to HDD and CDD from Northeast Regional Climate Center
- Projected changes to device efficiencies, and changes in shares of households using different cooking technologies from AEO 2020
- Estimated annual heat pump additions from VELCO/Itron, each displacing 40% of heat provided by a furnace or boiler (other devices meeting higher heating shares introduced in mitigation measures)
- GHG emissions from EPA's SIT

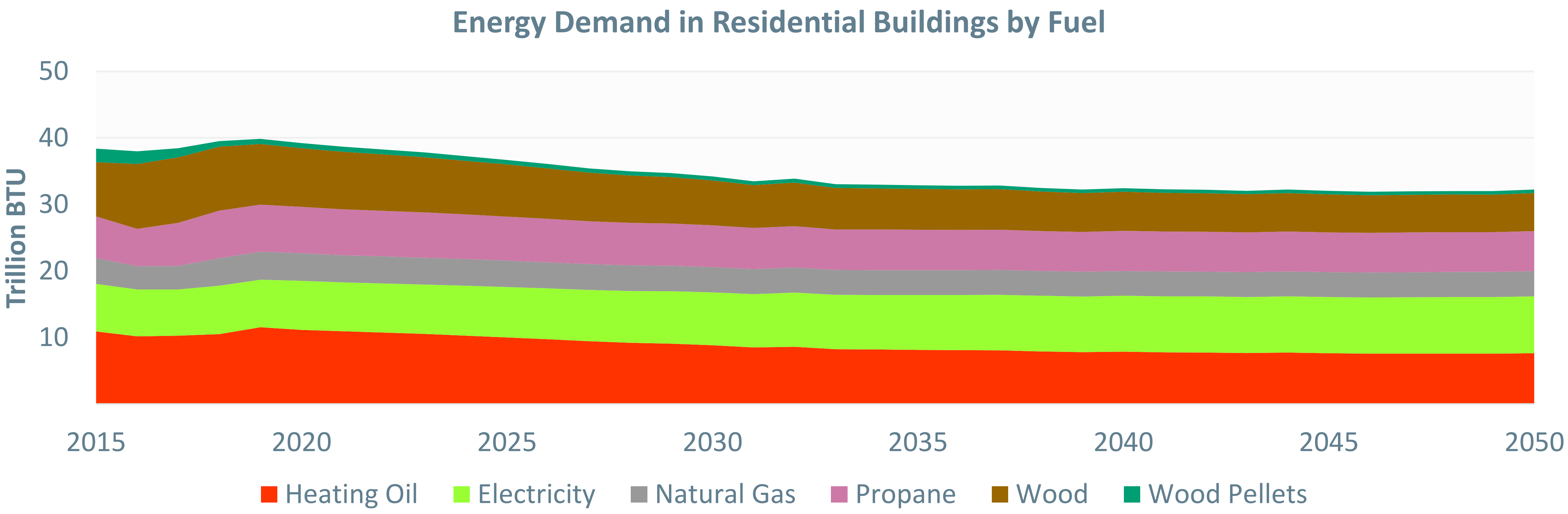
Residential Buildings: Business-as-Usual Assumptions



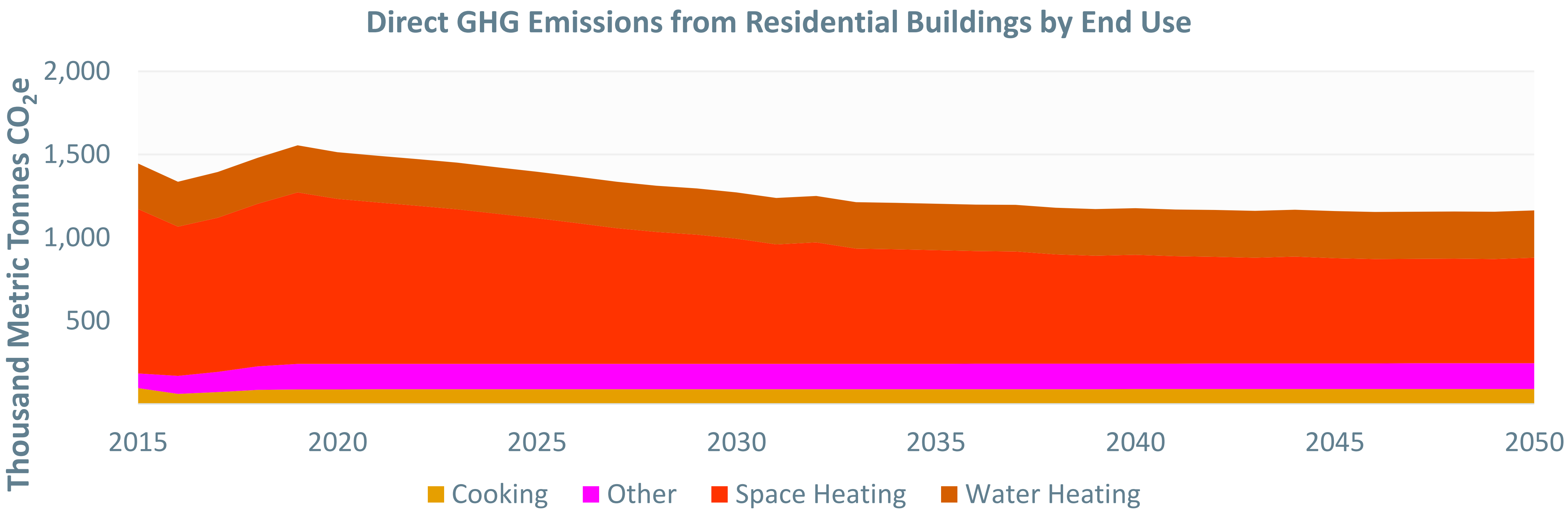
Residential Buildings: Business-as-Usual Results



Residential Buildings: Business-as-Usual Results



Residential Buildings: Business-as-Usual Results



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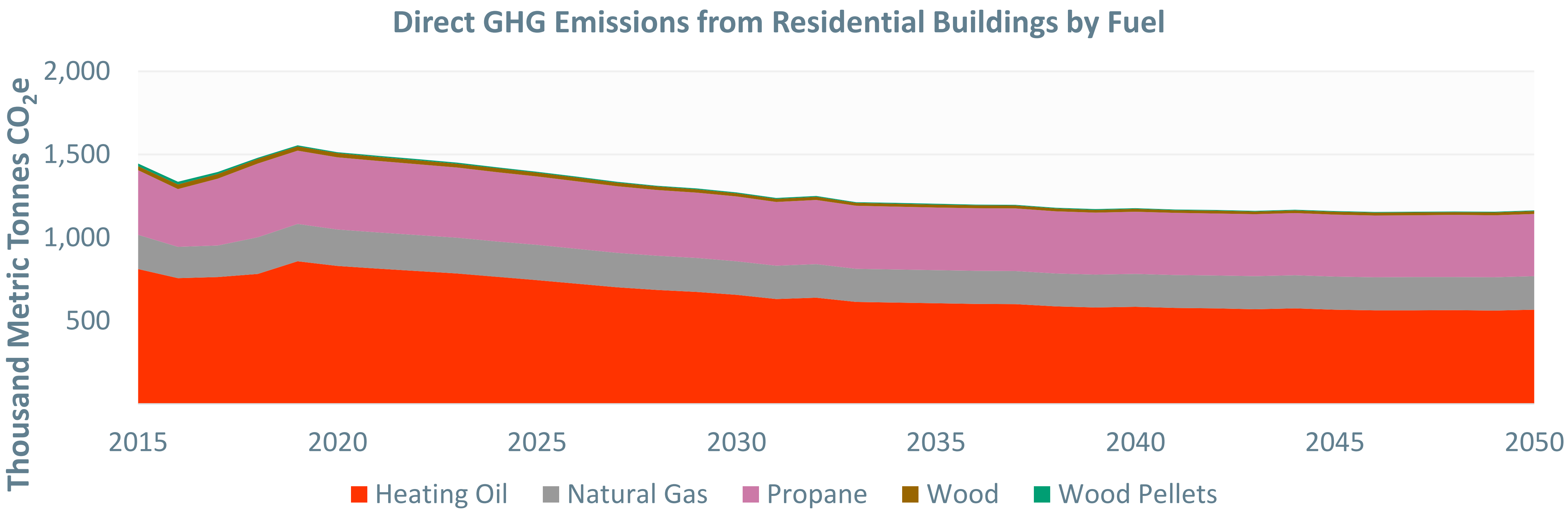
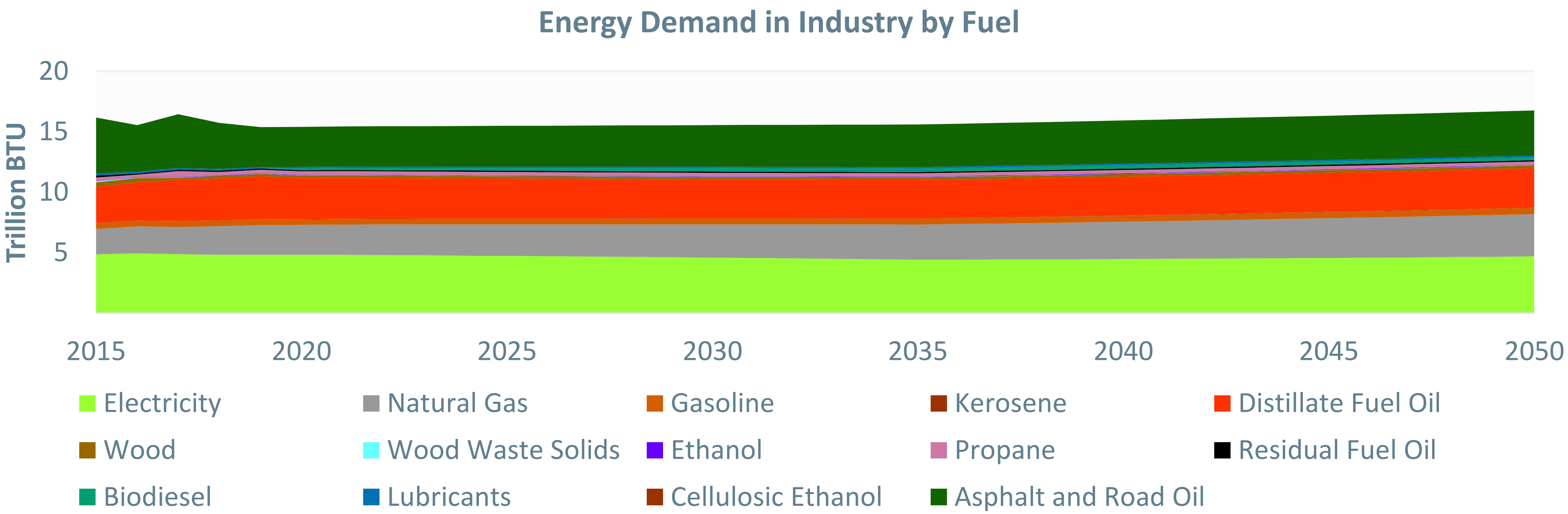


Industry

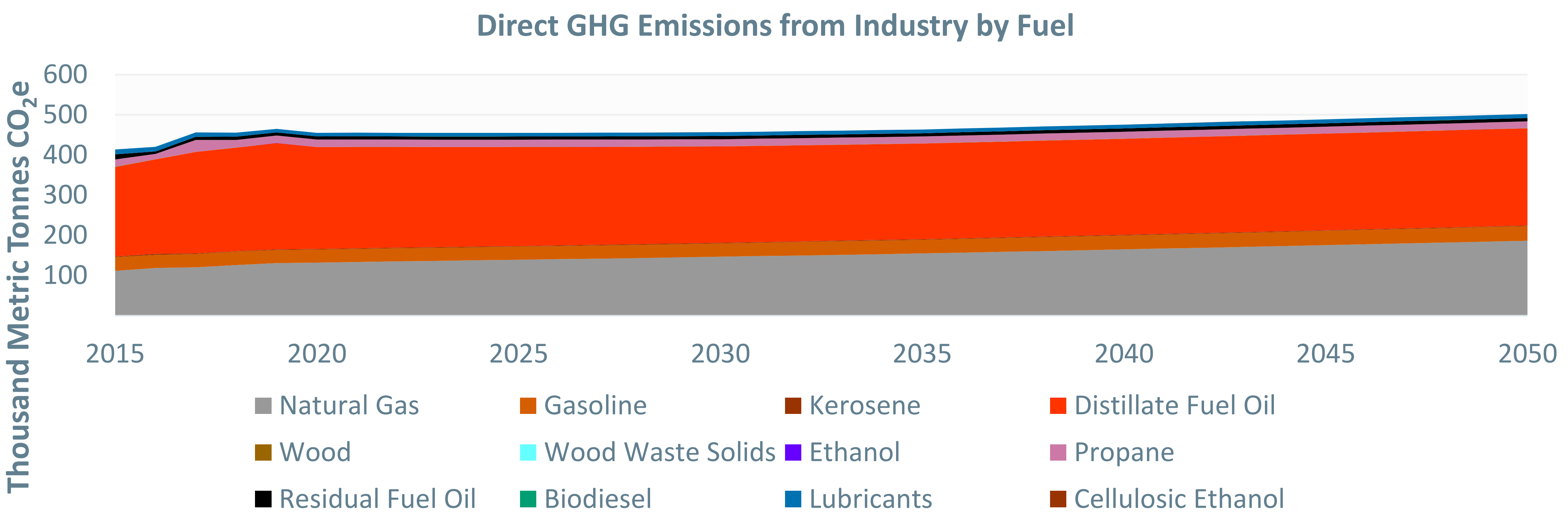
What's Included?

- Historical energy consumption by fuel from SEDS, with consumption forecasts aligned with AEO 2020
- AEO 2020: forecasted growth in final demands for each fuel
- Adjustments in natural gas, thermal fuels and electricity consumption to include forecasted energy efficiency programs from PUC and EVT
- GHG emissions from EPA's SIT

Industry: Business-as-Usual Results



Industry: Business-as-Usual Results



Electric Generation and Emissions: Methods

“Vermont-sized version of ISO – NE grid”

- Existing and planned Vermont plants and remainder of ISO – NE plants grouped separately, by technology
  - All on-grid capacity derated according to Vermont’s historical fraction of New England retail electricity sales (<5% of New England-wide sales)
- Imports grouped by origin (NY, QC, NB)
- Energy requirements are met in each “time slice”
  - 192 pseudo-hourly time slices per year: [24 hours] × [weekend vs. weekday] × [4 seasons]
  - Model estimates **consumption-based electricity emissions** by accounting for existing purchase contracts, before the remainder of uncontracted (rest-of-system) resources are dispatched to meet state demand
  - **Production-based emissions** may also be estimated, but not shown here

Electric Generation and Emissions: Methods

Least-cost capacity expansion and dispatch, under the following constraints:

- Demand (and 8% energy loss from transmission) satisfied
- Planning reserve margin maintained
- Sufficient renewable energy production to meet Vermont's Tier I and II RPS (no representation of RECs separately from renewable kWh)
- Existing energy purchase contracts enforced, assumed to expire on current end date

nemo **Calculations are performed using NEMO optimization software, integrated into LEAP**

Electric Generation and Emissions: Key Data and Forecast Sources

Existing and Planned Capacity: EIA-860 Form, Vermont SOP, ISO – NE BTM Forecast

Existing Purchase Contracts for Vermont Utilities: PSD

System Reserve and Capacity Adequacy: ISO – NE capacity supply obligations and net installed capacity requirement (NICR)

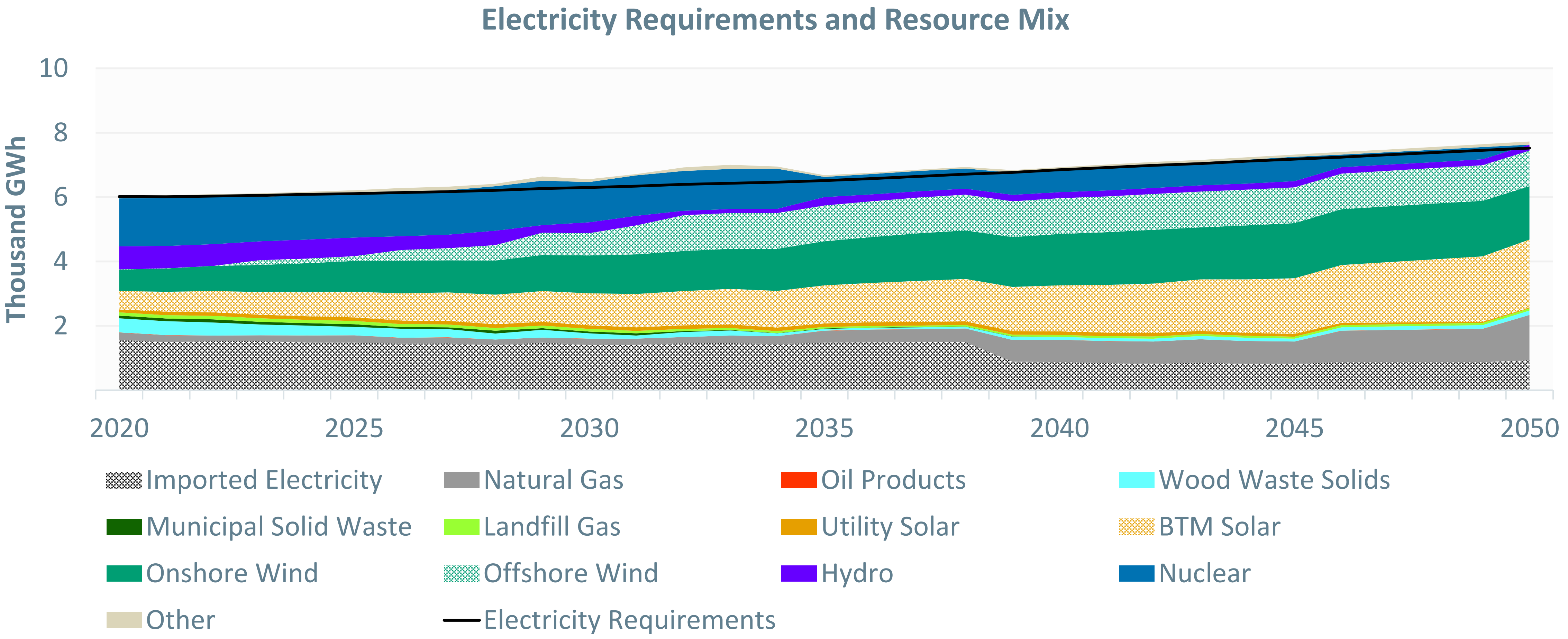
Plant Generation Characteristics: EIA-923 Form, various

Plant Costs: NREL, AEO, various

Current and Projected System Load *(used for all electricity consumption except heat pumps and electric vehicles)***:** ISO – NE loads

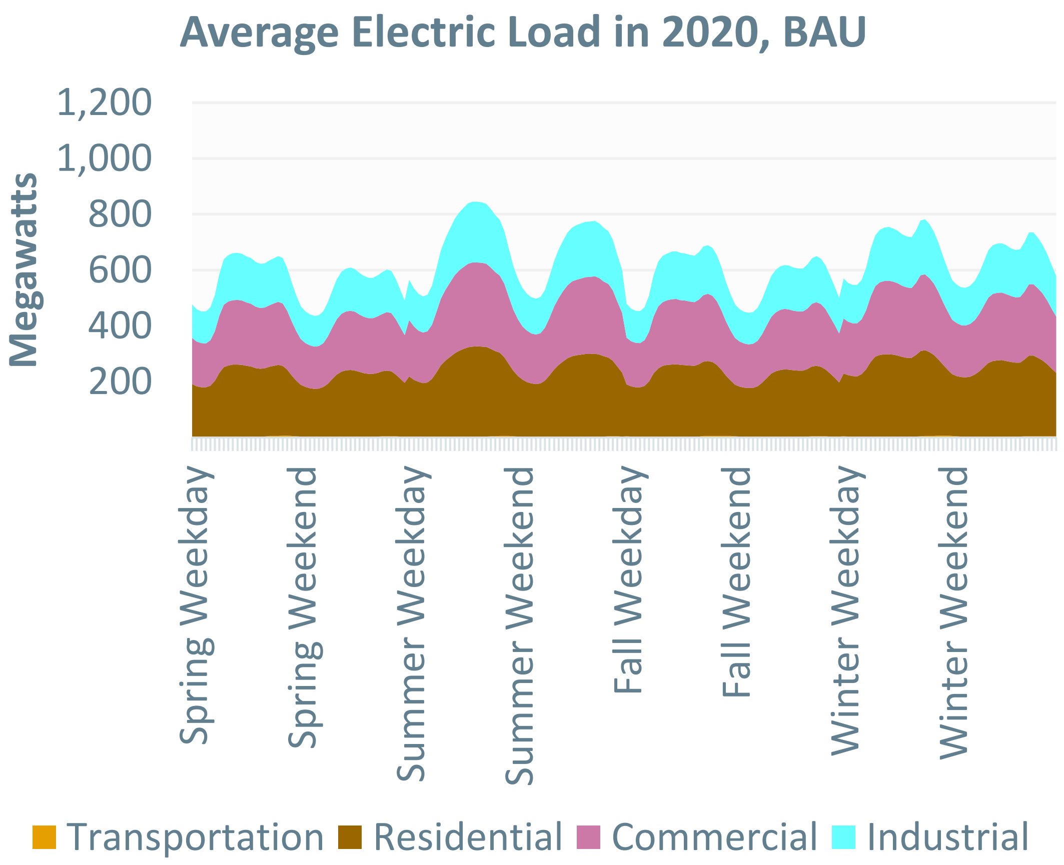
GHG Emissions: eGRID

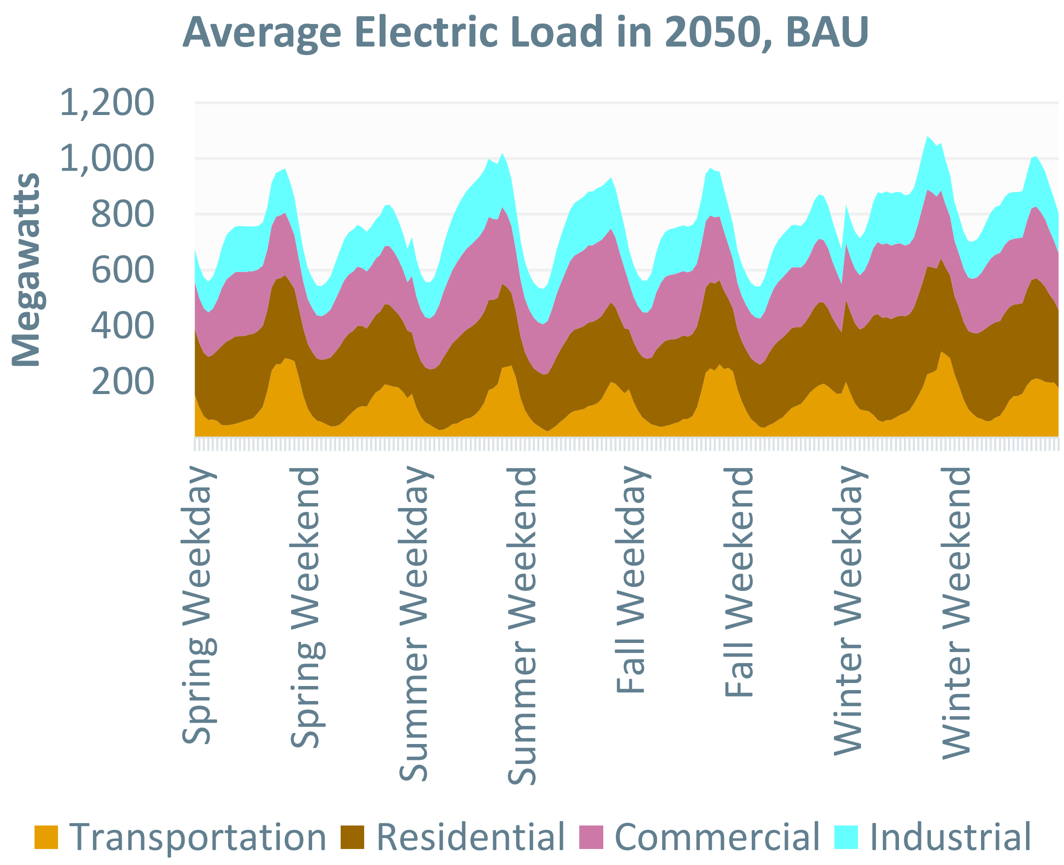
Electricity Mix in Business-as-Usual Scenario



* Electricity requirements illustrate Vermont demand plus transmission and distribution loss. Additional electricity production is considered surplus.

Detail: Sector Contributions to Electric Load





* Megawatts displayed show average power demand for each time slice, **gross** of BTM solar.

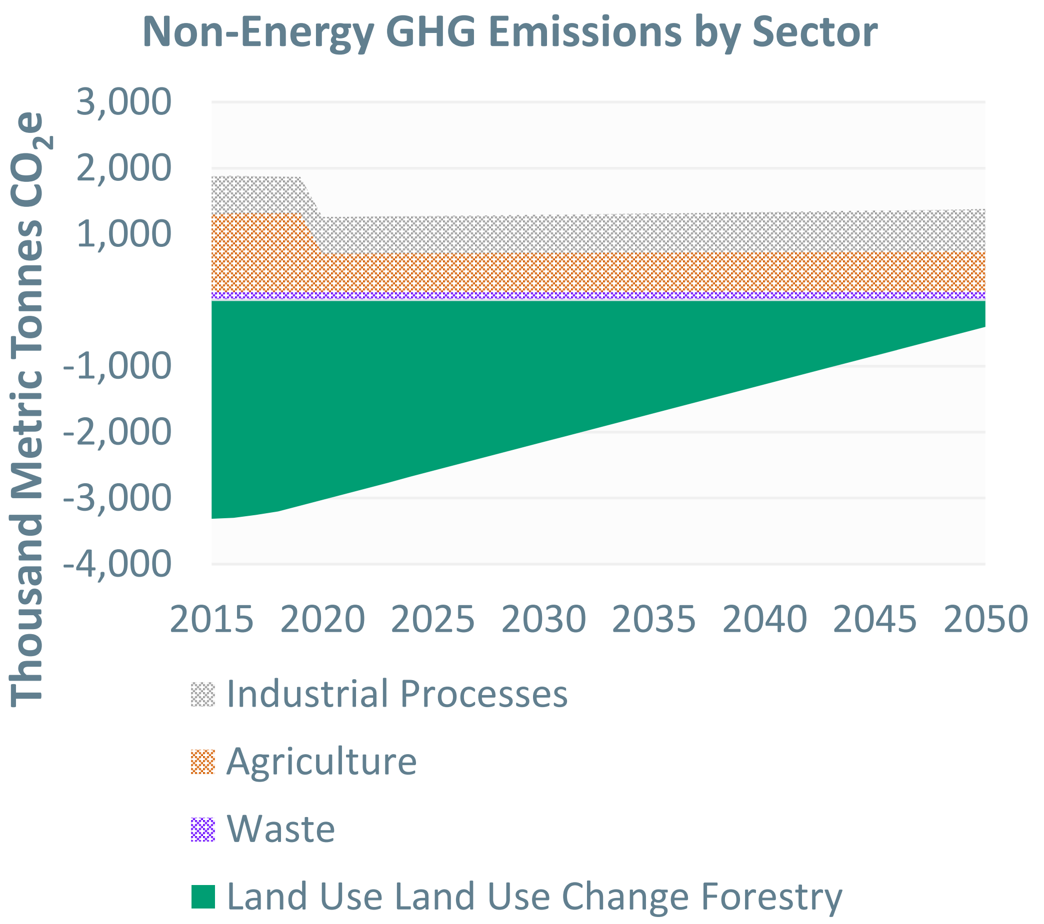
Electricity Modeling: Interpretation Notes

Since Vermont's electricity supply comes from a mix of regional and local sources, some choices have been made to present Vermont-specific electricity sector results.

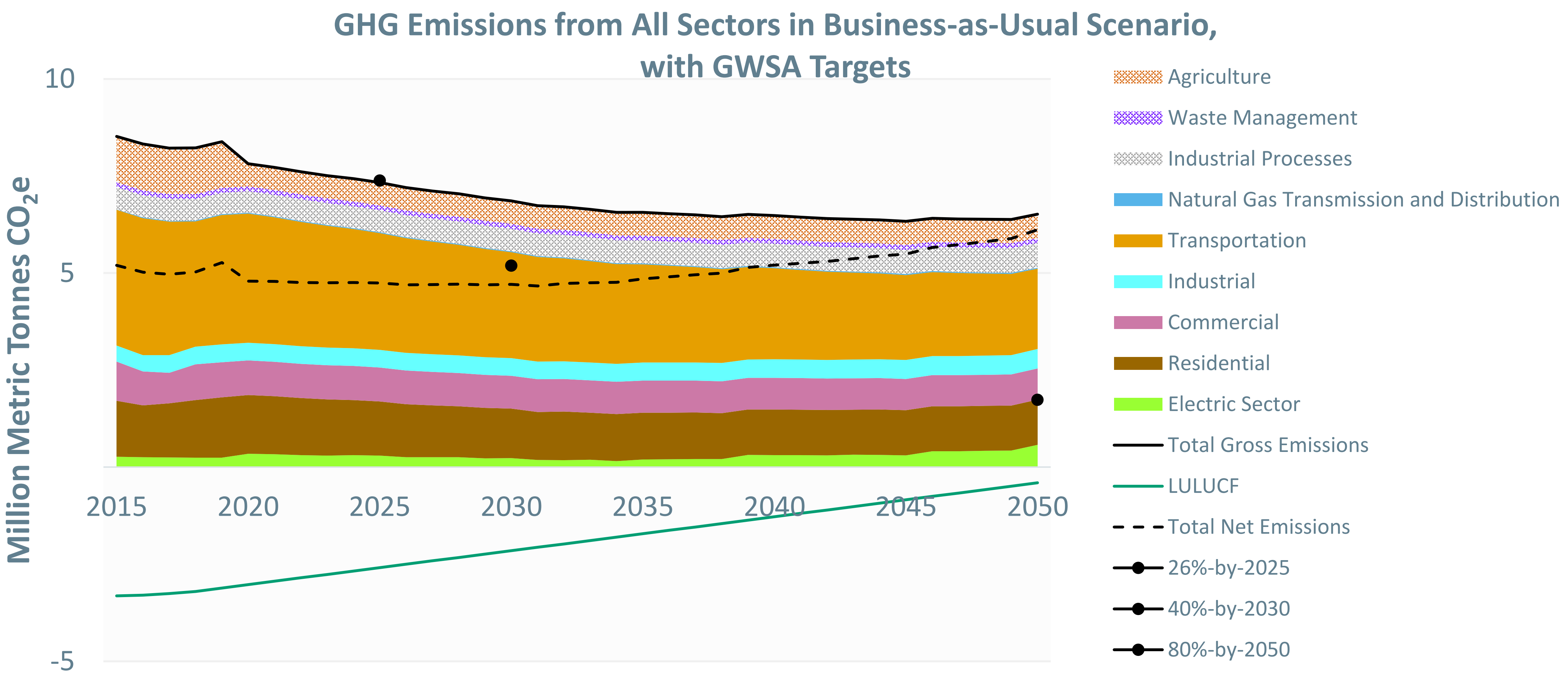
- **BTM Solar:** Treated as a supply resource, *not a load reducer*. 100% of Vermont-located BTM PV capacity is used to meet Vermont electricity requirements, but only a portion of rest-of-ISO BTM PV capacity meets Vermont's needs through the (uncontracted) system mix.
- **On-Grid Capacity:** Installed capacity used to serve Vermont is the minimum of a) derated capacity (roughly 5% of nameplate) or b) whatever is necessary to fulfil existing energy procurement contracts (up to 100% of nameplate. *This can make modeled capacity results difficult to interpret, so they are not presented.*

Non-Energy GHG Emissions Baseline

- Historical emissions from EPA's SIT default data for Vermont, and AQCD
- Forecasts developed by indexing emissions to state population, or, using historical average growth rates observed within a given subsector
- Further adjustments to historical and forecasted emissions in LULUCF and agriculture from EFG/Cadmus



GHG Emissions, Business-as-Usual



Inclusion of Non-GHG Emissions

- Emission factors specified as mass per unit of energy consumed, or per distance of vehicle travel
- GHG emissions expressed as mass of each GHG, or in CO_2-equivalent with any choice of Global Warming Potential (GWP, IPCC Fourth Assessment Report values used by default)
- Non-GHG criteria emissions and other air pollutants expressed as mass of each individual pollutant
- Wide range of data sources are used, including IPCC, EPA SIT, AP42, eGRID, GREET, SEI, NESCAUM, EMEP/EEA

Pollutant	Details of inclusion in model
CO_2 from fossil fuels, CO_2 from biogenic sources, CH_4, N_2O	Included for all sectors and fuels
CO	Included for all sectors and fuels
NO_2 or NO_x, depending on detail provided in source	Included for all sectors and fuels
SO_2	Included for all sectors and fuels
PM2.5	Included for all sectors and fuels
Lead	Included only for combustion of coal, oil, wood/wood waste, and MSW for power generation
Non-methane VOCs	Included for all sectors and fuels
O_3	Not included explicitly; both NOx and NMVOC emissions included instead
Black carbon	Included for all liquid transport fuels, all fuels consumed in households, and all remaining wood and biomass combustion
Other toxics	Not included

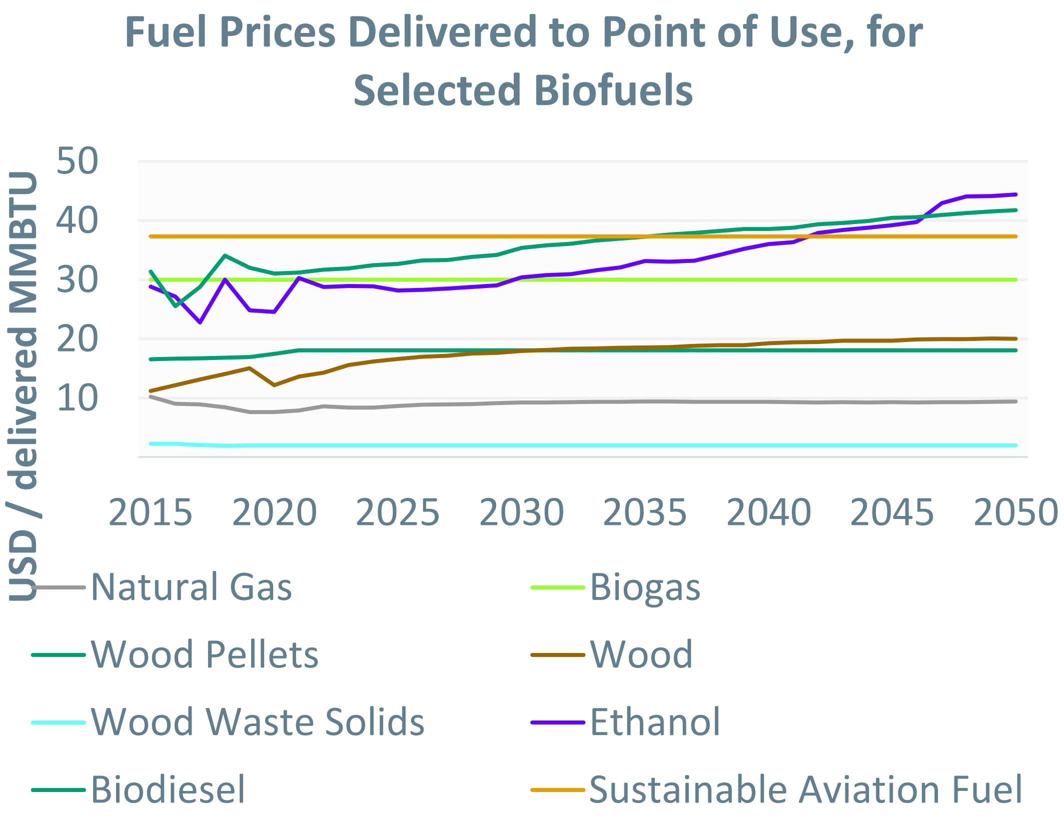
Cross-Cutting Cost Assumptions

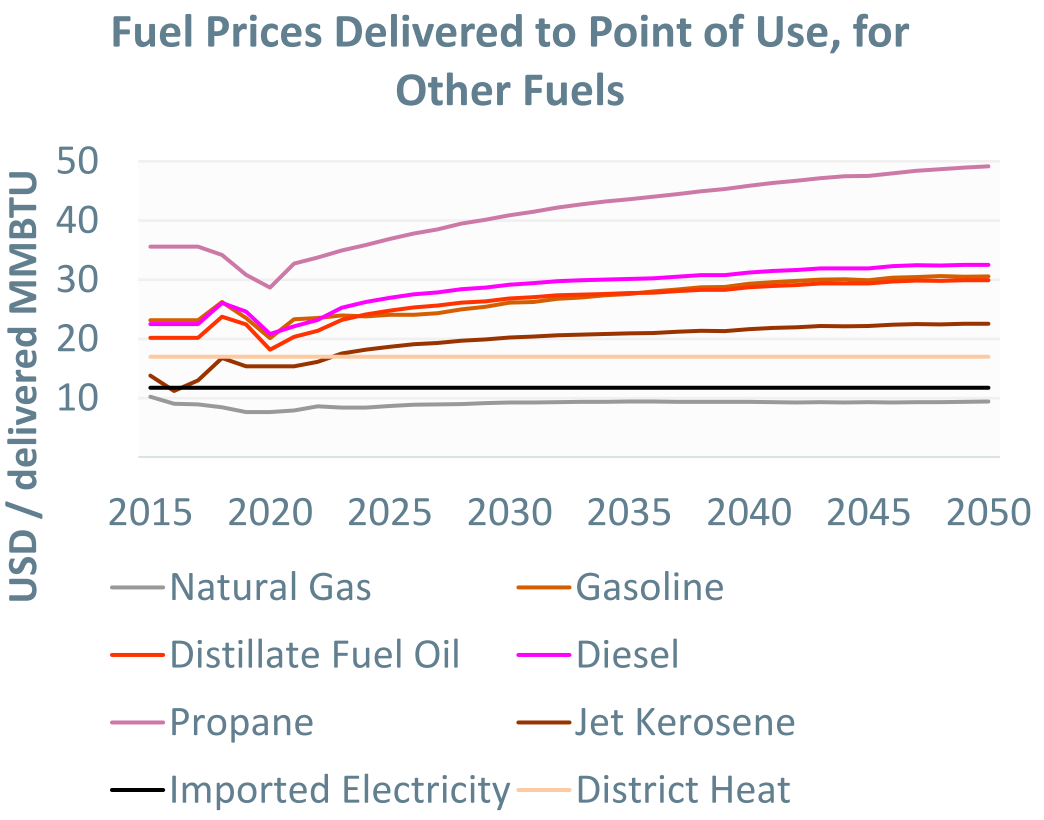
General Treatment of Costs in Modeling

Scenarios may be compared by their energy requirements, emissions of GHGs and other pollutants, and by their costs (or benefits) relative to one another

- Some costs are specified uniquely within some scenarios, or only for technologies/end-uses that vary across scenarios
  - Permits cost-benefit comparisons between two scenarios.
- Other cost inputs (such as fuel supply costs) are included for all scenarios, allowing the model to calculate differences internally. **These are cross-cutting cost assumptions.**

Fuel Costs for all Scenarios



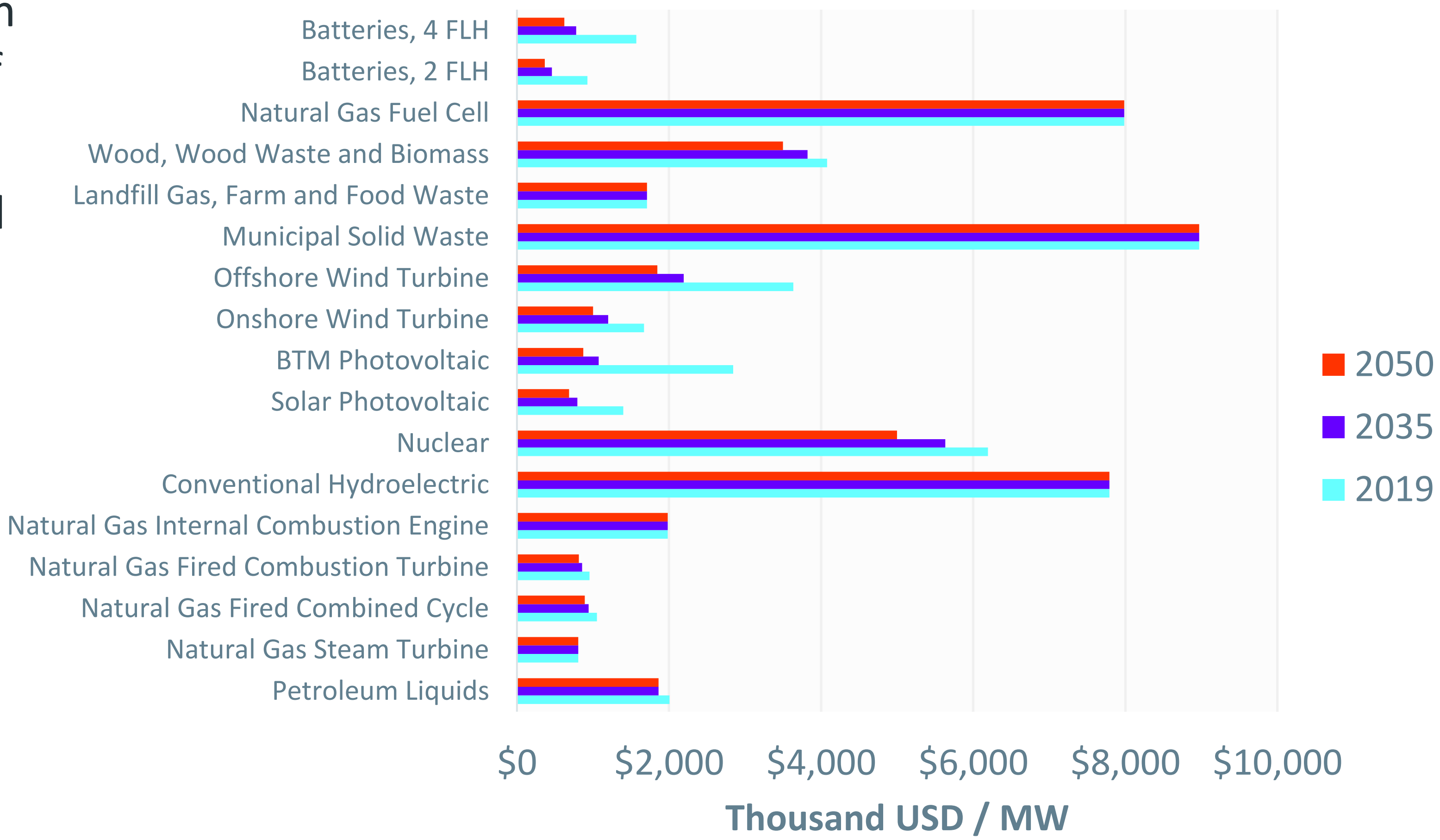


* For comparison, the natural gas price is shown in both charts.

Electric Sector Costs for all Scenarios

- Electricity pricing is endogenous in the model: depends on the mix of power plants and plant dispatch
- Each technology assigned unitized capital, operation & maintenance costs
- Additional system-wide $84/kW$_{peak}$ assumed for transmission and distribution upgrades
- Capital costs are overnight and include grid connection

Electric Generation Capital Costs



* FLH = full-load hours, the number of hours at rated output capacity that a battery may provide

Monetary Year

- All costs are expressed in real 2019 US dollars unless otherwise specified (conversions performed using US BEA data)
- Where applicable, present values of future costs are discounted to 2019 monetary year at 2%/year

Individual Mitigation Options

…next, *Mitigation Scenarios*

Organization of this Section

- For consistency, individual mitigation options are characterized using three categories: **saturation, performance, cost**
- Limited business-as-usual (baseline, BAU) assumptions are provided as counterfactuals for mitigation scenario changes (BAU assumptions subject of earlier presentations)

	Scenario Changes	Business-as-Usual Comparison
Saturation	• How much of the new measure or technology is in this scenario? By when?	• What does the measure displace? What was the business-as-usual assumption?
Performance	• What are the energy or environmental attributes of the new technology?	• How well did the alternative technolog(y/ies) perform?
Cost	• What cost assumptions are assigned in this scenario? What are the costs or savings of the new technologies relative to business-as-usual?	• What were the cost assumptions for displaced technologies?

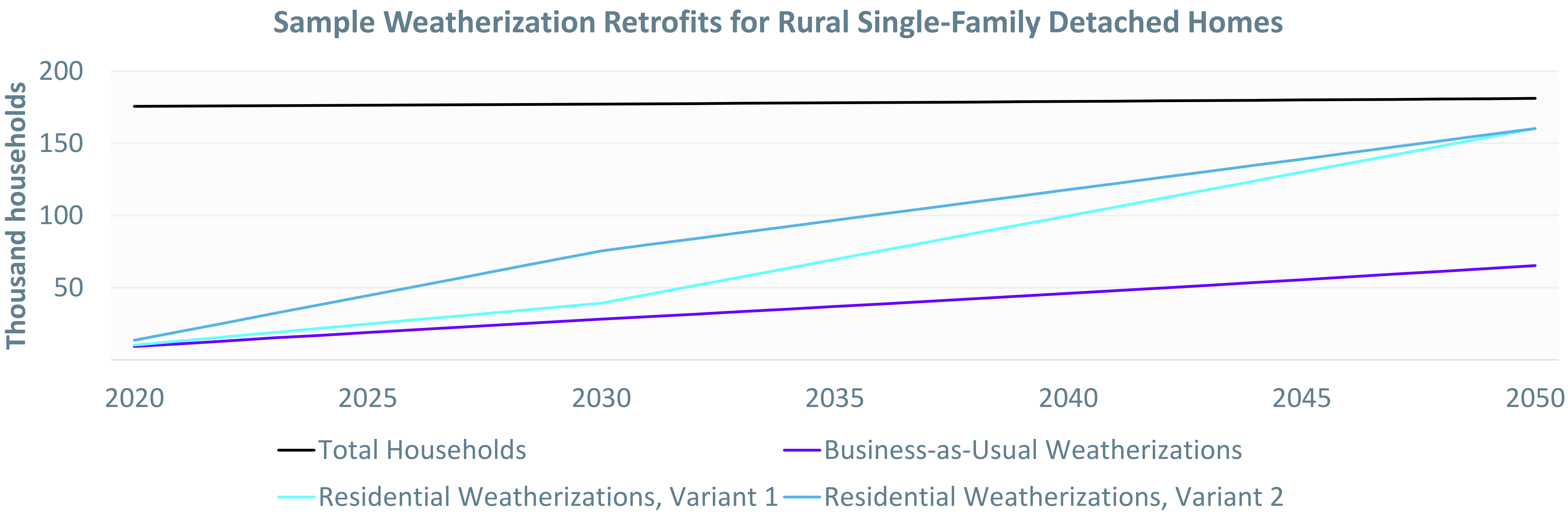
Residential Building Shell Improvements

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** 72k cumulative retrofits by 2030, 243k retrofits by 2050, aligned with 10,770 retrofits/year by 2040 based on EVT "High Scenario" weatherization forecast and VGS forecast • **Variant 2:** 120k retrofits by 2030 based on "Weatherization at Scale" initiative, 243k retrofits by 2050	• 86,700 cumulative residential retrofits by 2050, aligned with 2,435 retrofits/year reached by 2040 from EVT "Low Scenario" weatherization forecast and VGS forecast • Includes multi-family (3E Thermal) and single-family retrofits (from EVT, BED, VGS and low income)
Performance	• Weatherizations result in average *useful energy** savings (from reduced air leakage, etc.) of 20% and 38%, for single- and multi-family households respectively, assumed based on PSD_1	
Cost	• Average weatherization retrofit cost $7,405/single-family household, $6,000/apartment (2-4 units), $3,000/apartment (5+ units) based on PSD_2	

* Useful, or "delivered" energy, refers to the heat energy required to maintain an interior temperature. It is different than the final energy (gas, oil, electricity) consumed in a building.

Detail: Residential Weatherization

Example of rural housing type



Heat Pumps for Residential Space Conditioning

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** By 2040, high-efficiency air- and ground-source heat pumps (ASHPs and GSHPs) supply 80% of home heating needs • **Variant 2:** Heat pumps meet 70% of home heating needs by 2045	• Approximately 127k heat pumps deployed by 2050 (mix of ducted, single- and two-head mini-splits with total heating load equivalent to 90% that of VELCO “medium” forecast) • Residential heat pumps are 89% air-source, remainder ground-source • Centrally-ducted ASHPs provide 100% of displaced heat load provided by gas, oil and propane furnaces • Single- and two-head heat pumps displace remaining heating technologies, providing 40% and 66% (respectively) of displaced heating load

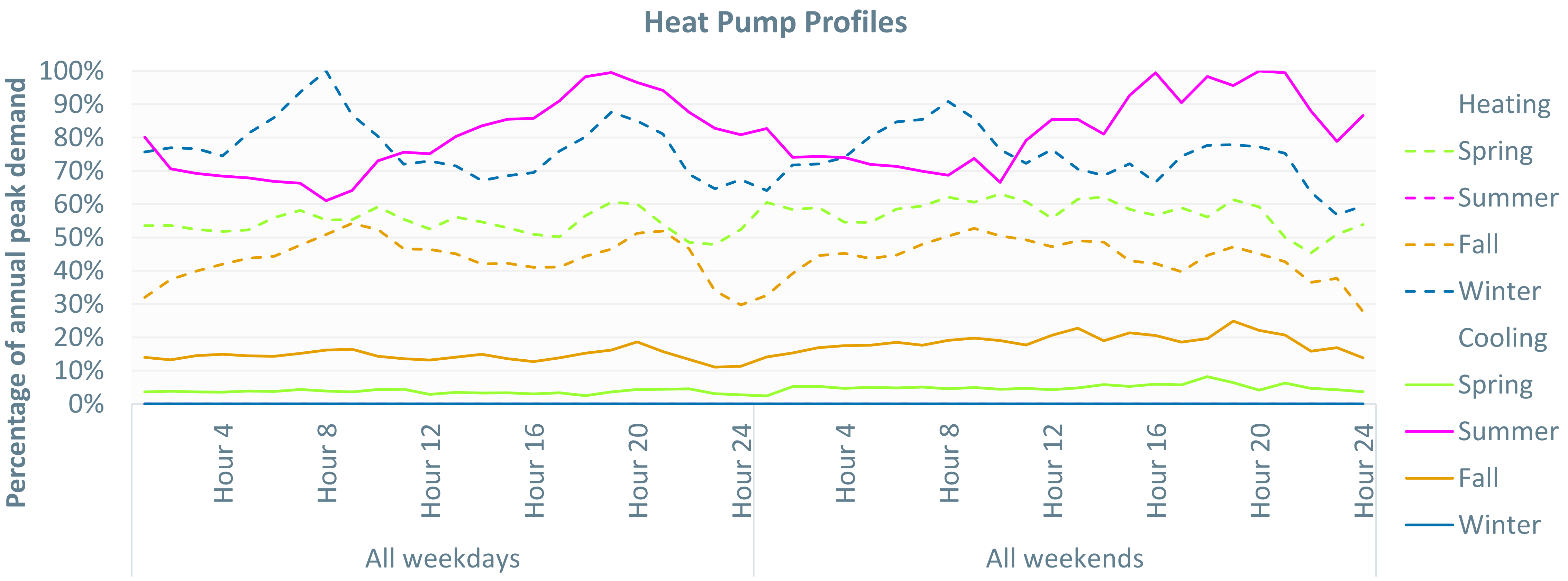
Heat Pumps for Residential Space Conditioning

	Scenario Changes	Business-as-Usual Comparison
Performance	• Single-head and ducted ASHP COP of 2.6, two-head ASHP COP of 2.3, GSHP COP of 4.5	
Cost	• Single- and two-head ASHP installed cost of $6,100 and $7,000 respectively, lasting 15 years with annual maintenance of $72.5 • Ducted ASHP installed cost of $8,500, lasting 18 years with annual maintenance of $72.5 • GSHP installed cost of $17,050, lasting 14 years with annual maintenance of $75	

Heat Pumps for Commercial Space Conditioning

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** By 2040, air-source heat pumps heat 80% of commercial floorspace • **Variant 2:** Heat pumps meet 70% commercial heating needs by 2045	• Approximately 24k heat pumps deployed by 2050 (total heating load equivalent to 10% that of VELCO “medium” forecast) • Commercial heat pumps from VELCO forecast are entirely air-source • Commercial ASHPs provide 100% of displaced heat load provided by gas, oil and propane boilers
Performance	• Average energy consumption per device 2,085 kWh/year (heating mode) and 146 kWh/year (cooling mode) • Commercial heat pumps consume 16-27 kBTU/ft^2, depending on building shell	
Cost	• Commercial heat pump serving 3000 ft^2 installed cost of $7,550, lasting 21 years with annual maintenance of $310	

Detail: Heating and Cooling Energy Use



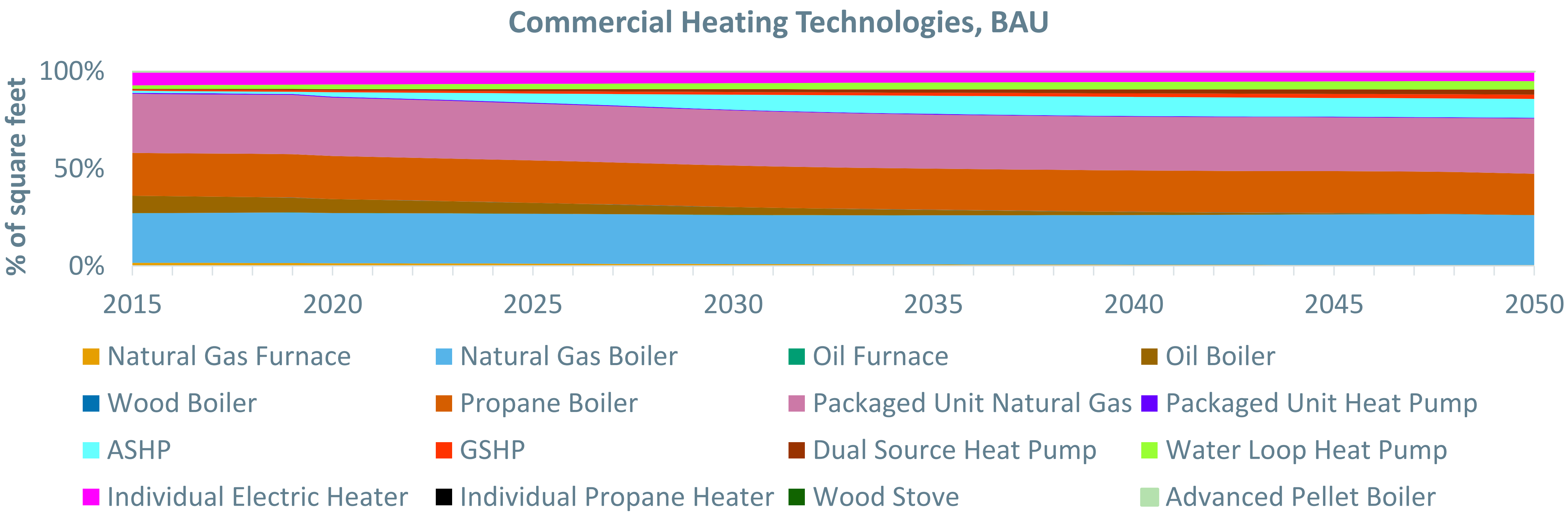
Advanced Wood Heating

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** By 2045, advanced pellet boilers replace 20% of residential and commercial propane and oil boilers • **Variant 2:** Advanced pellet boilers replace 25% of residential and 30% of commercial propane and oil boilers • For existing buildings (classified as households built after 2015 and commercial floorspace added after 2007), pellet boilers displace only 90% of the alternative	• No advanced pellet boilers
Performance	• Advanced pellet boilers are 86% efficient • In commercial sector, this translates into 76-95 kBTU/ft^2, depending on building shell	
Cost	• Residential pellet boiler installed cost of $20k, lasting 20 years with annual maintenance of $250 • Commercial pellet boiler installed cost of $65k, lasting 20 years with annual maintenance of $250, per 6900 ft^2 commercial space	

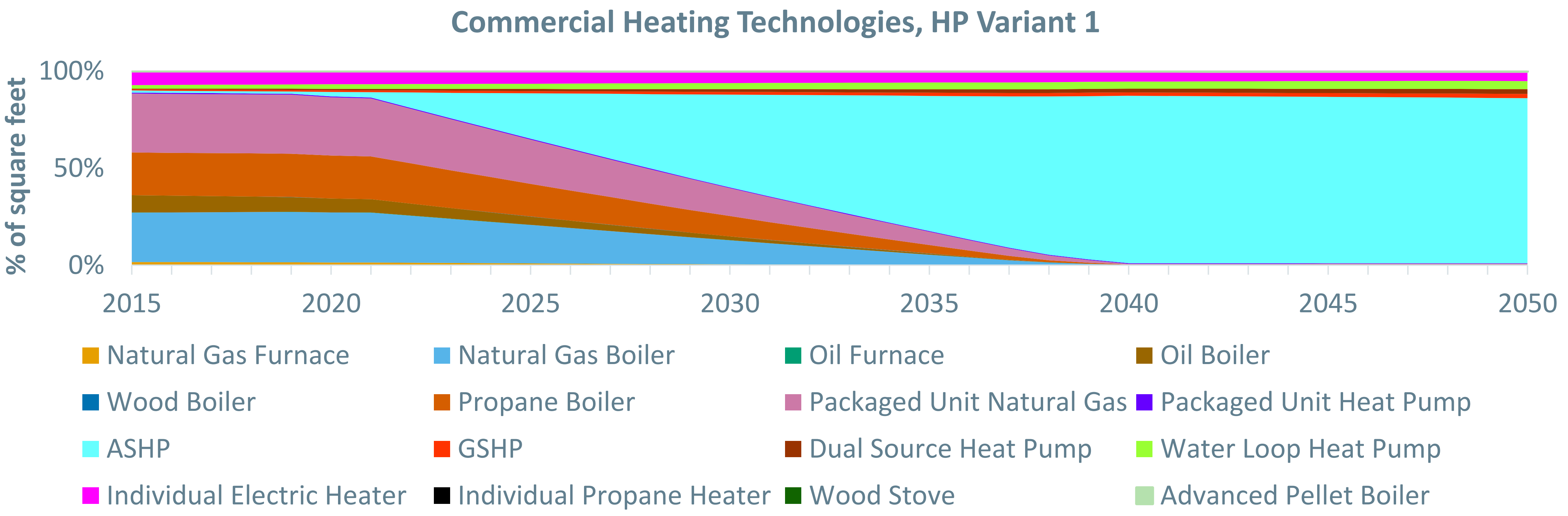
Commercial District Heating

	Scenario Changes	Business-as-Usual Comparison
Saturation	• In 2027, McNeil generating station captures 170,000 MMBTU/year waste heat for commercial sector use • Additional dedicated wood waste heat plants are added in 2030, 2035 and two in 2040, each producing 170,000 MMBTU/year	• No district heating.
Performance	• Dedicated heat production is 86% efficient, neglecting distribution loss	
Cost	• Heat delivered through district heating network costs 17 USD/MMBTU	

Detail: Commercial Heating Technologies



Detail: Commercial Heating Technologies



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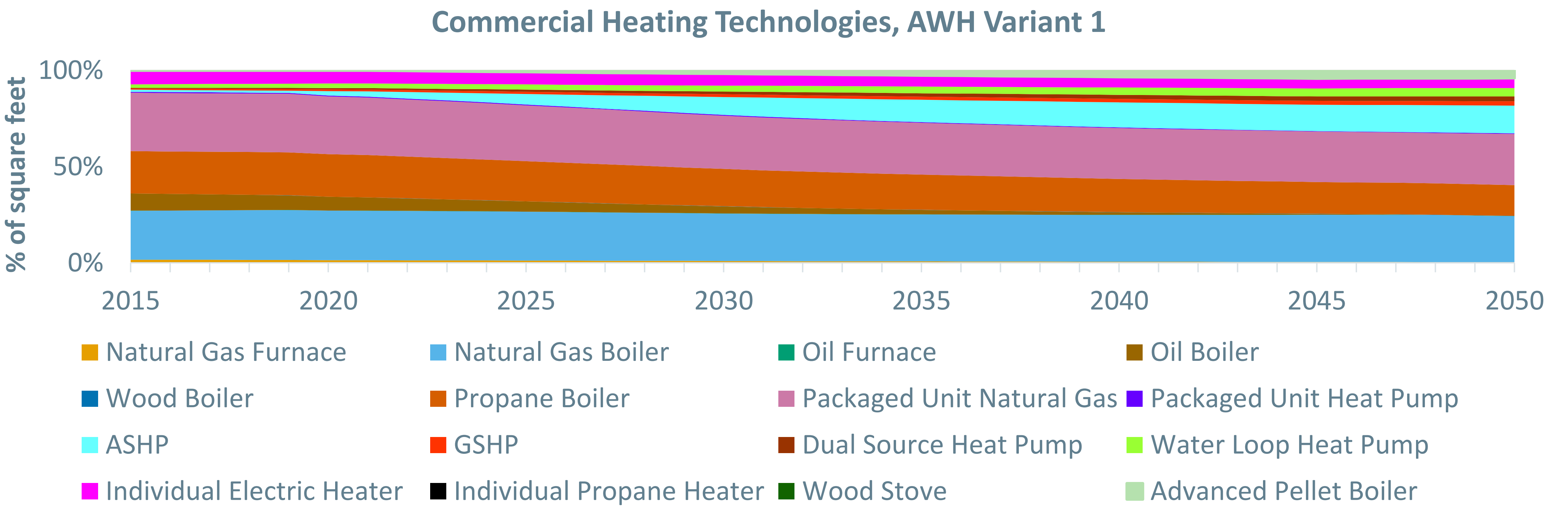
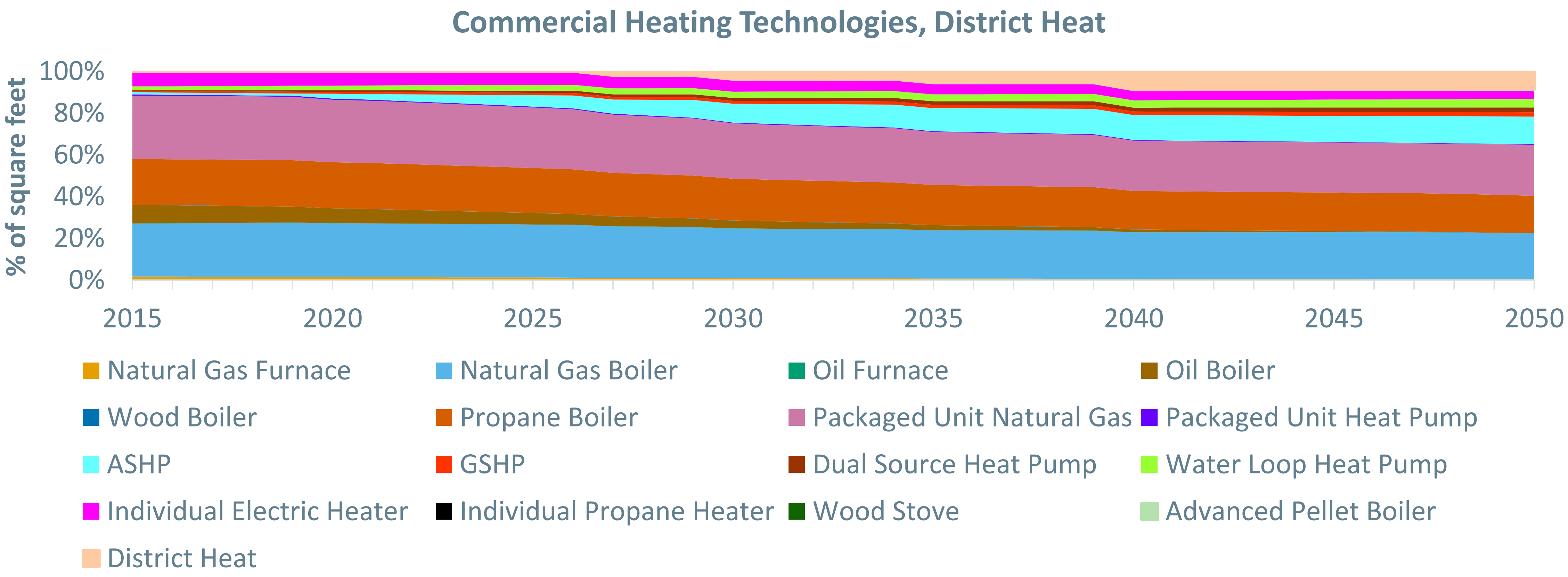
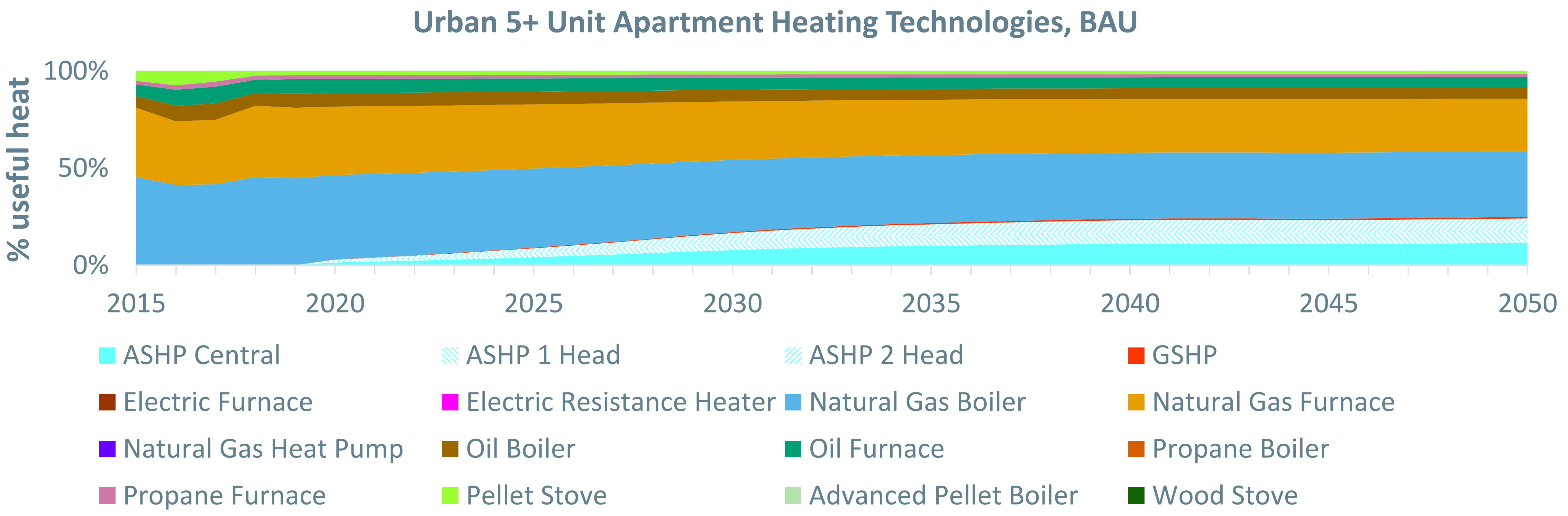


Detail: Commercial Heating Technologies



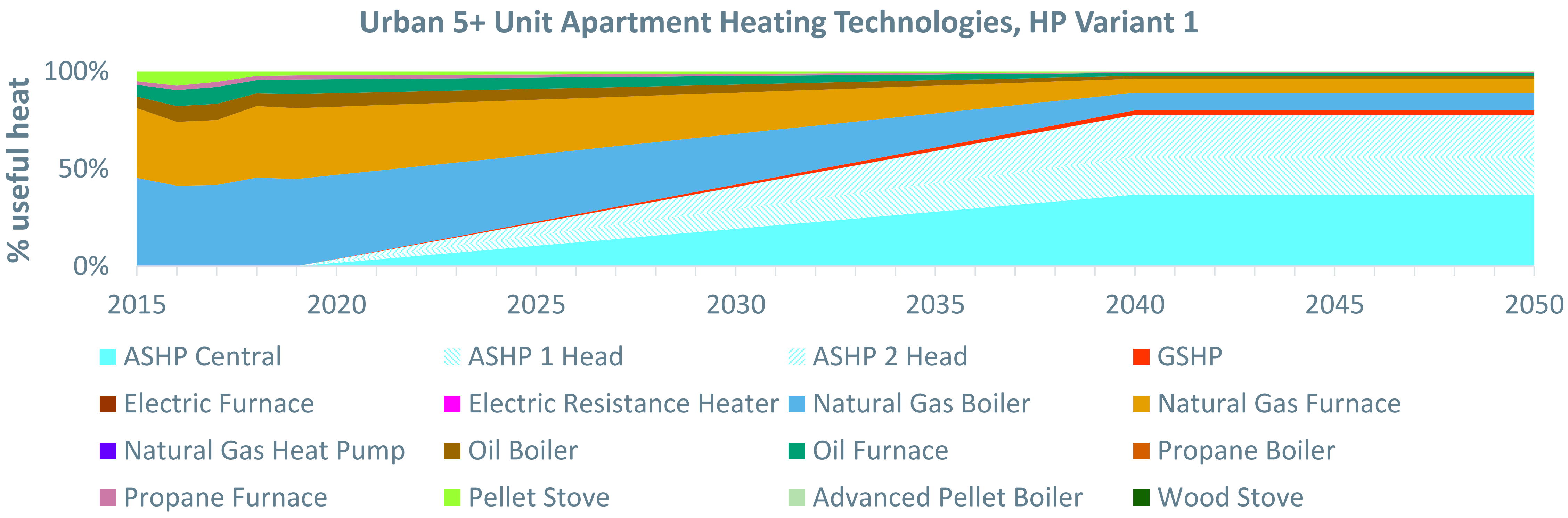
Detail: Residential Heating Technologies

Example of urban housing type



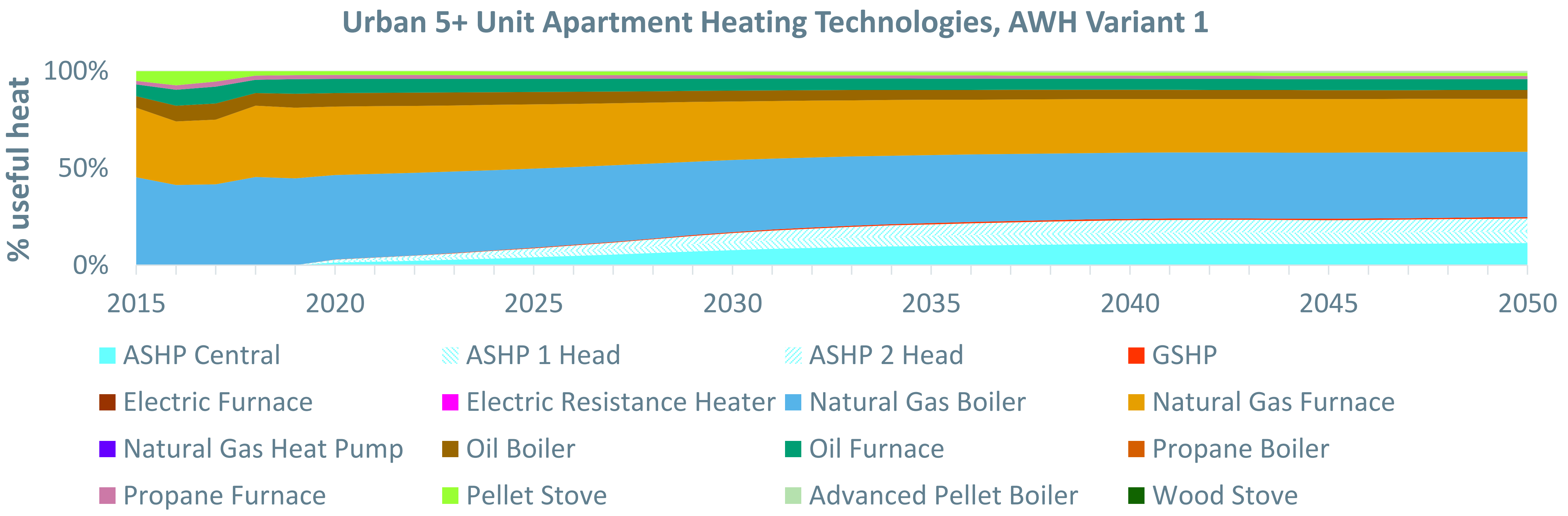
Detail: Residential Heating Technologies

Example of urban housing type



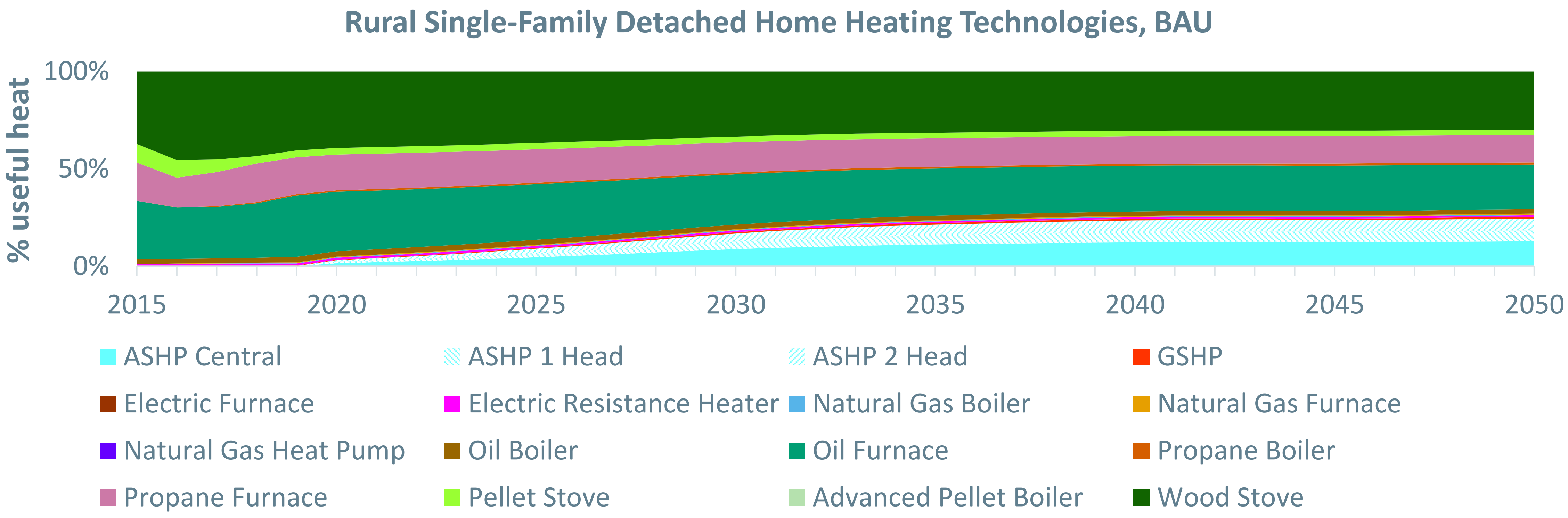
Detail: Residential Heating Technologies

Example of urban housing type



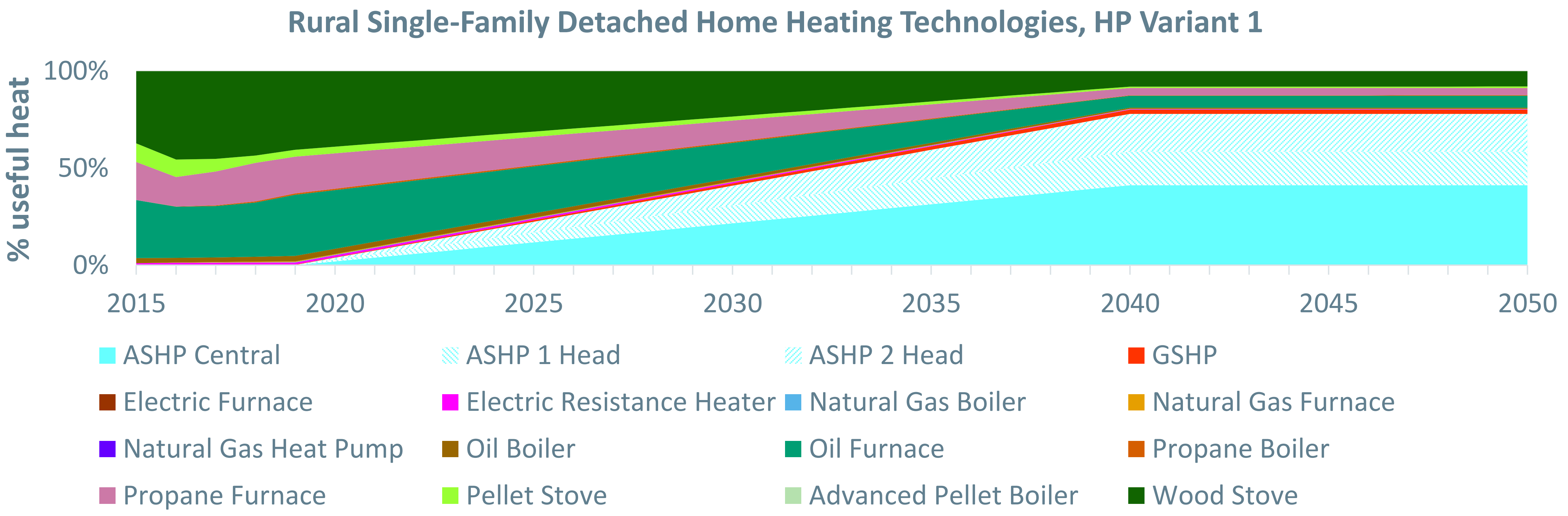
Detail: Residential Heating Technologies

Example of rural housing type



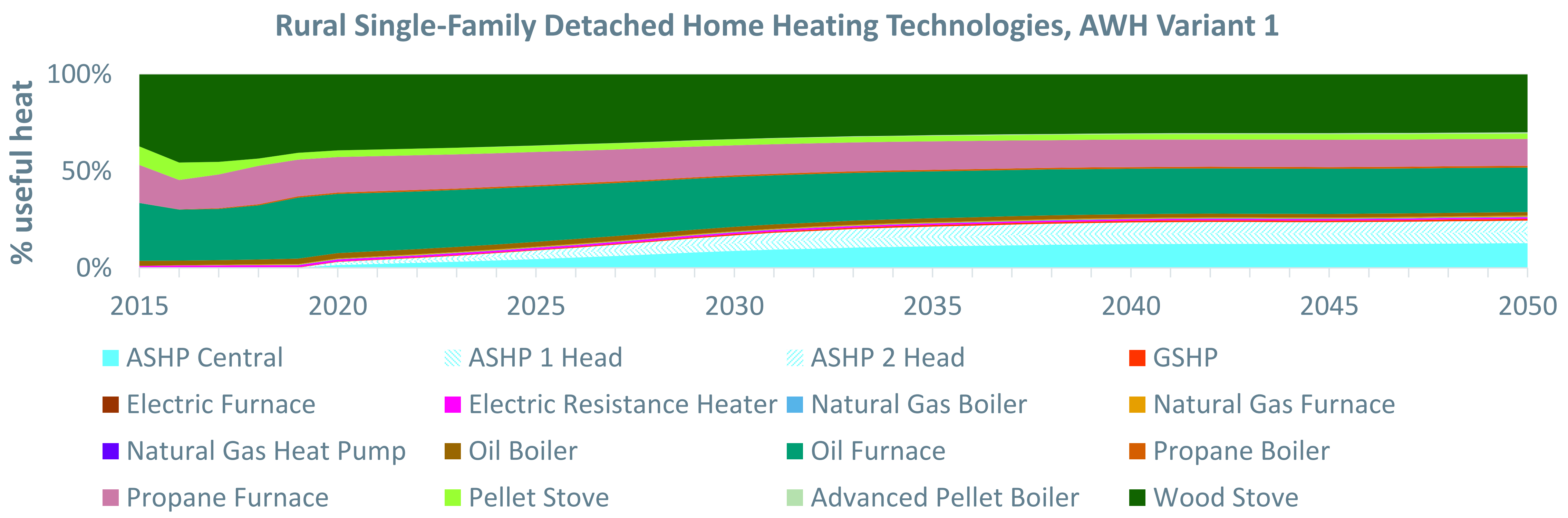
Detail: Residential Heating Technologies

Example of rural housing type



Detail: Residential Heating Technologies

Example of rural housing type



Heat Pumps for Water Heating

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2035, hot water heat pumps (HWHPs) meet all household and commercial water heating needs previously met by fossil fuels	• 0.2-6.5% of household water heating needs met by heat pumps, depending on building type, no change over time • No commercial hot water heat pumps
Performance	• High-efficiency residential hot water heat pump COP of 3.55 • Commercial hot water heat pumps consume 4.9 kBTU/ft^2, reaching 4.3 kBTU/ft^2 by 2050	
Cost	• Residential high-efficiency HWHP installed cost of \$2,475, lasting 13 years with annual maintenance of \$20 • Commercial HWHP serving 11,695 ft^2 installed cost of \$50,950, lasting 15 years with annual maintenance of \$100	

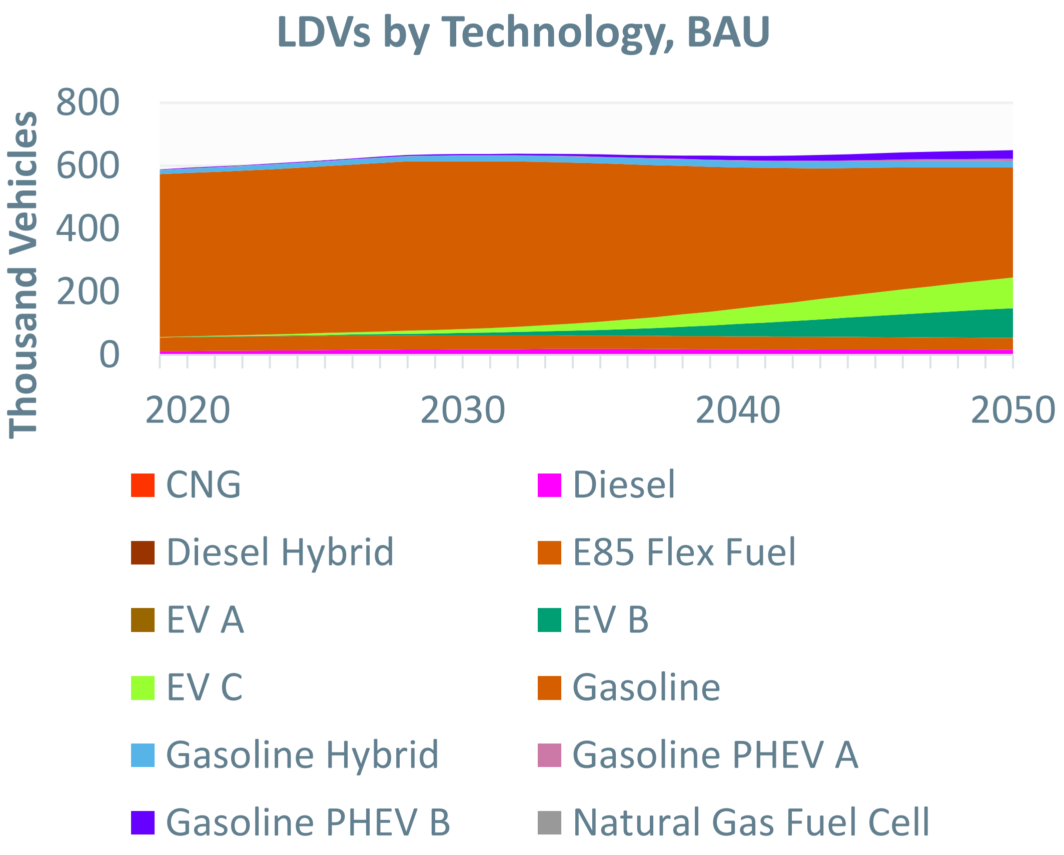
Clean Cooking

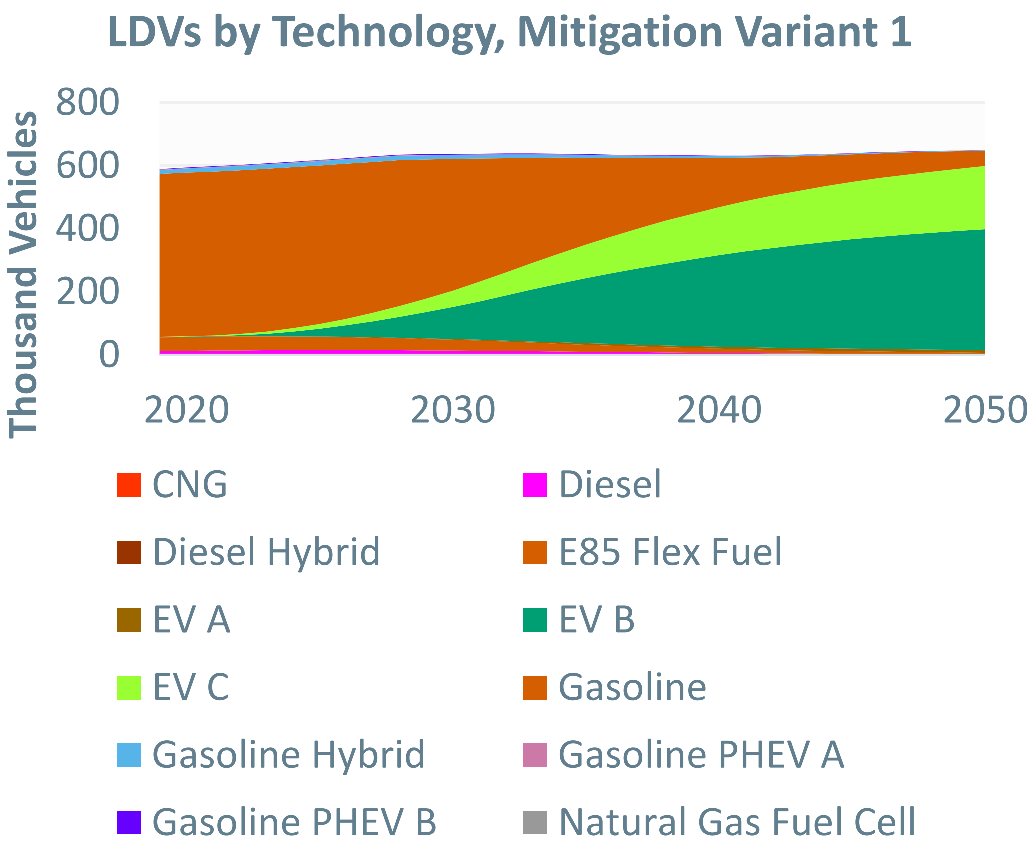
	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2035, electricity replaces fossil fuels for cooking in residential and commercial buildings	• Electric stoves and ovens in 48-100% of households, depending on building type • 41% of commercial space uses electric cooking appliances • Little or no change over time
Performance	• Households consume 186-584 kWh/year, depending on building type • On average, commercial buildings consume 0.8 kWh/ft^2, reaching 0.5 kWh/ft^2 by 2050	
Cost	• Equipment cost difference between stove types assumed to be negligible; costs arise entirely from differences in fuel costs	

Phasing Out Internal Combustion Engines

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** By 2033, all sales of new on-road vehicles are battery electric vehicles (BEVs) • **Variant 2:** All sales of new on-road vehicles are BEVs by 2040 • For light-duty cars and trucks, BEVs are divided among 100-, 200- and 300-mile ranges	• Sales remain modest: by 2050, only 41% of light-duty sales and 7.5% of medium- and heavy-duty sales are BEVs • Based on VELCO "low" EV forecast, electrifying 35% of vehicles by 2050
Performance	• Electric vehicles consume less energy per mile than their fossil-fuel counterparts	
Cost	• Individual technologies in each weight class are assigned separate costs (light-duty EV cost examples shown on subsequent slides)	

Detail: Light-Duty Cars and Trucks by Technology

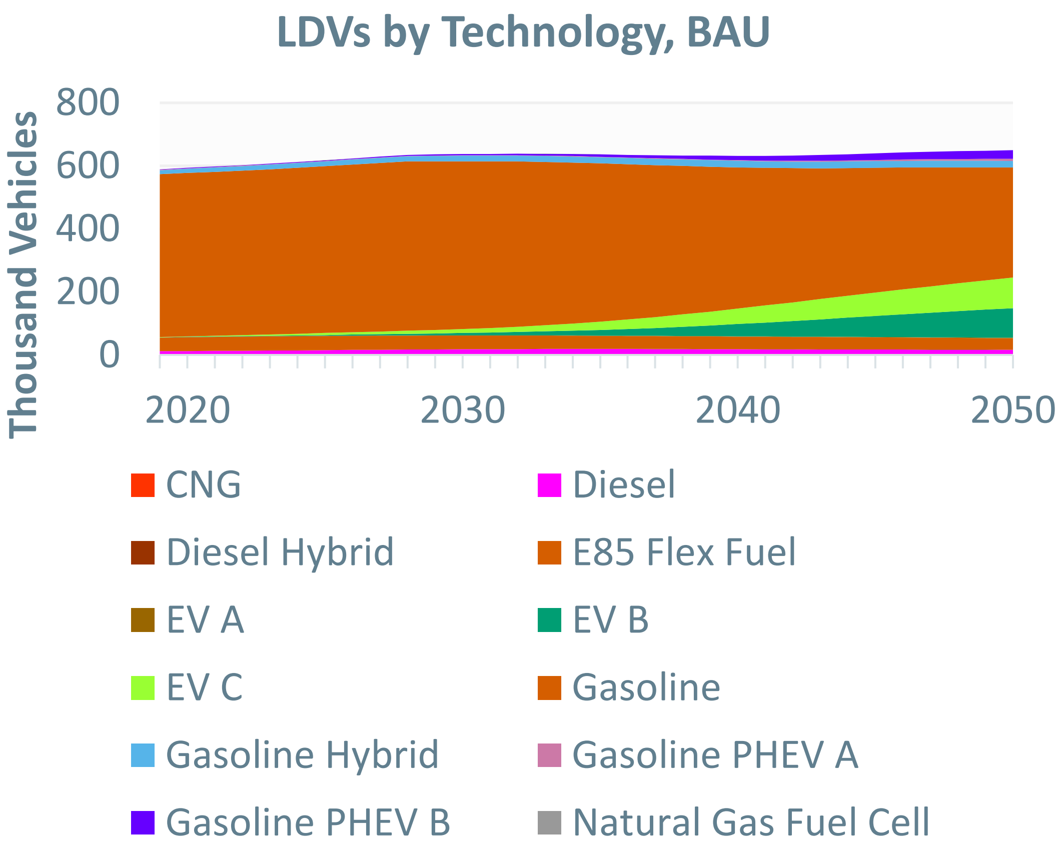


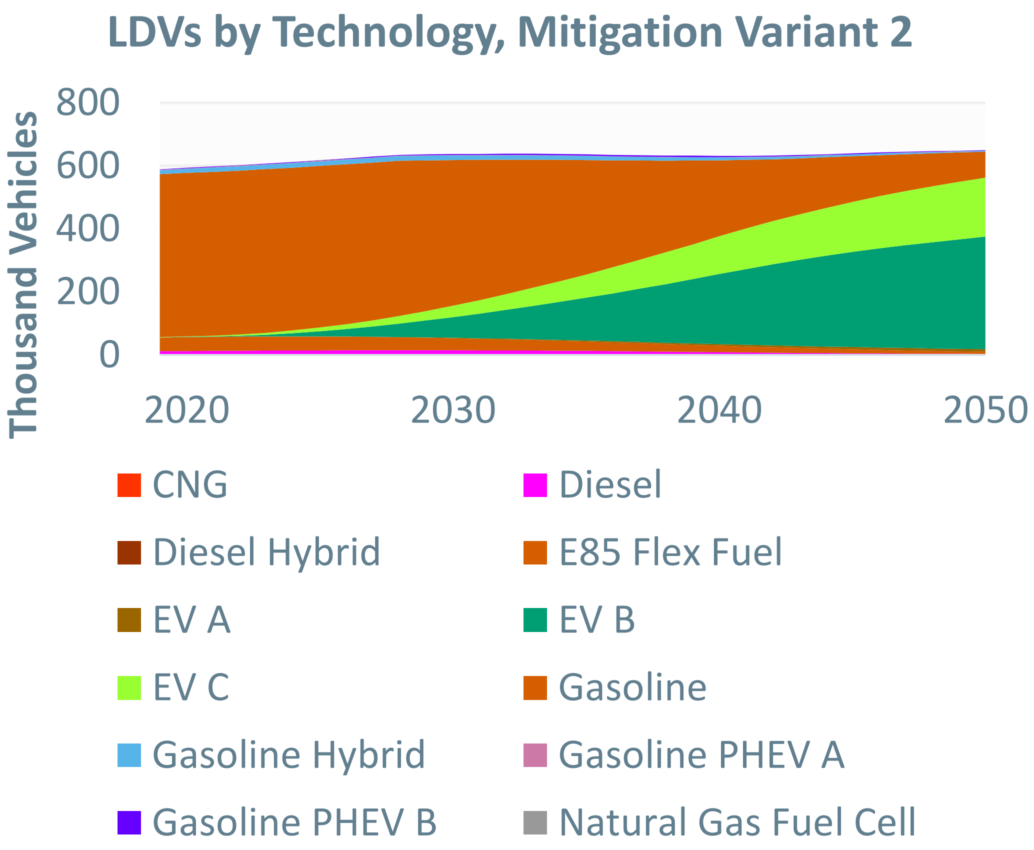


EV A/B/C = battery electric vehicles with range up to 100/200/300+ miles.

PHEV A/B = plug-in hybrid vehicles with electric range 10+/40+ miles

Detail: Light-Duty Cars and Trucks by Technology

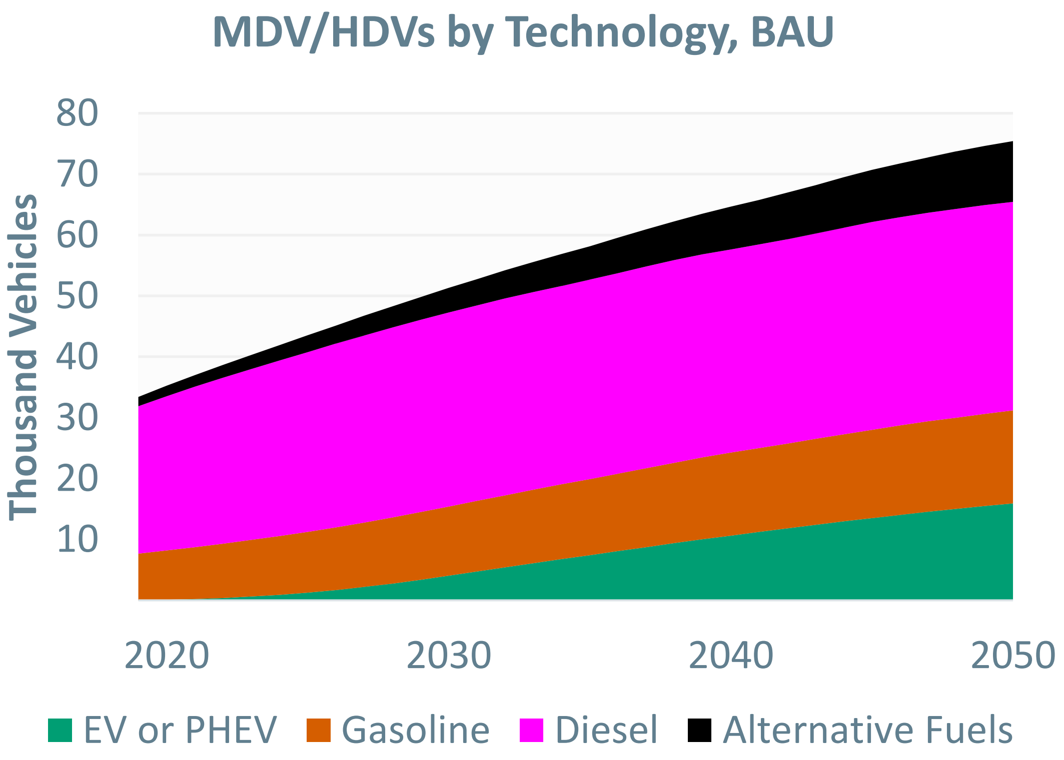


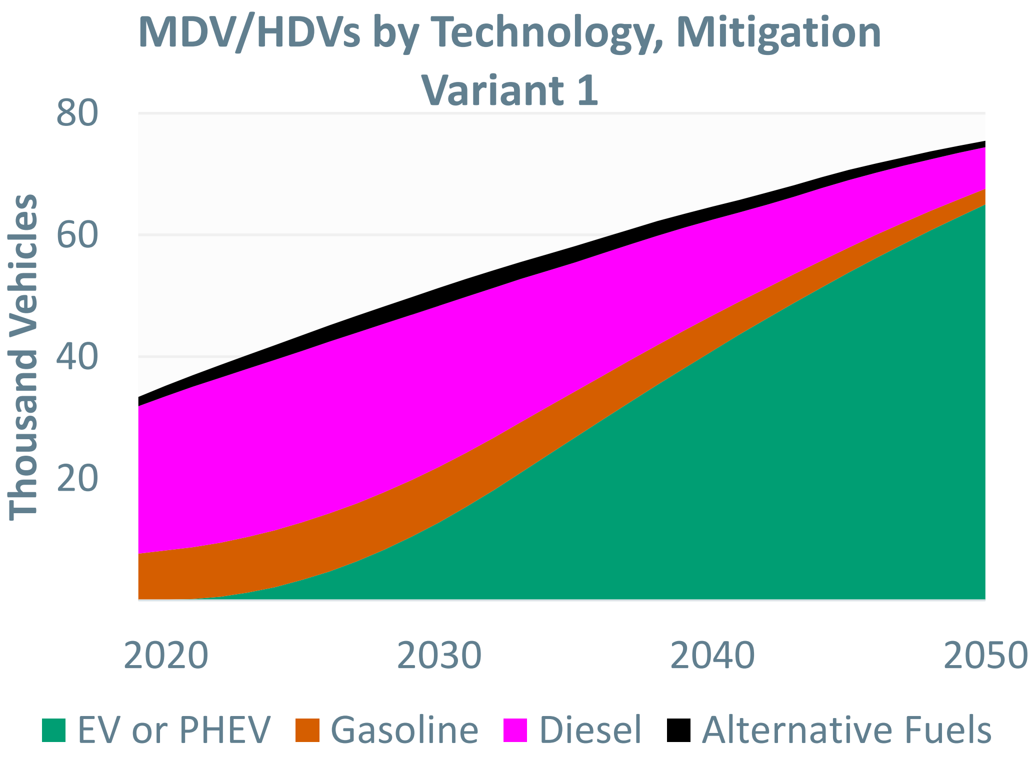


EV A/B/C = battery electric vehicles with range up to 100/200/300+ miles.

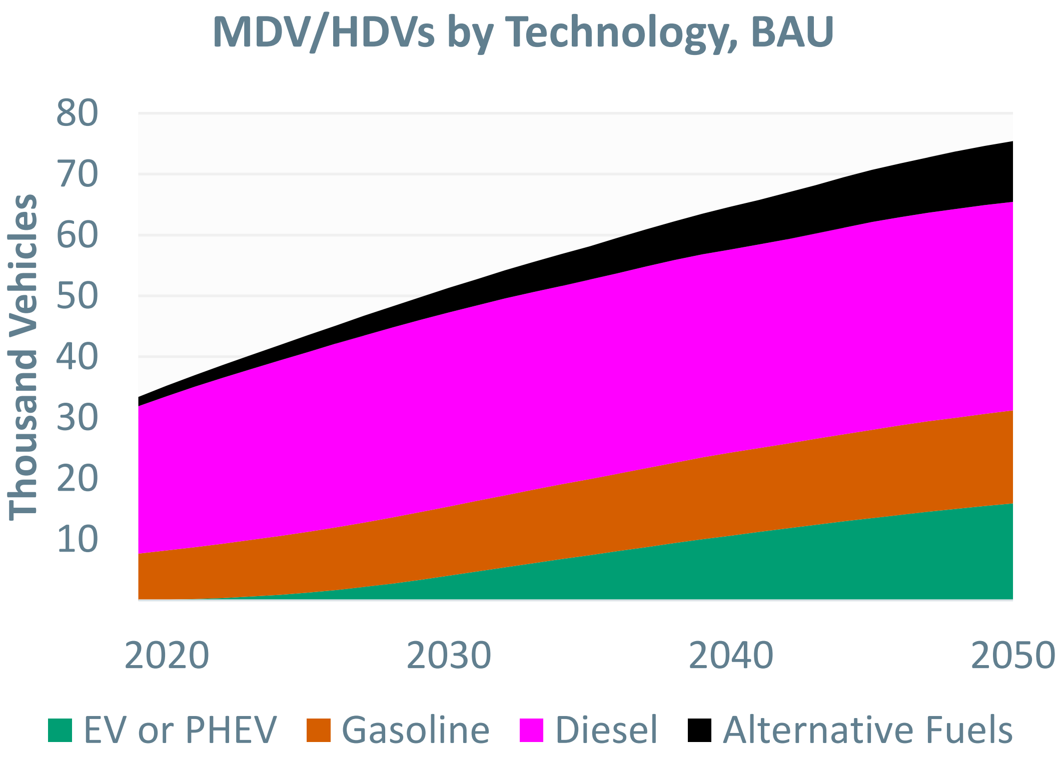
PHEV A/B = plug-in hybrid vehicles with electric range 10+/40+ miles

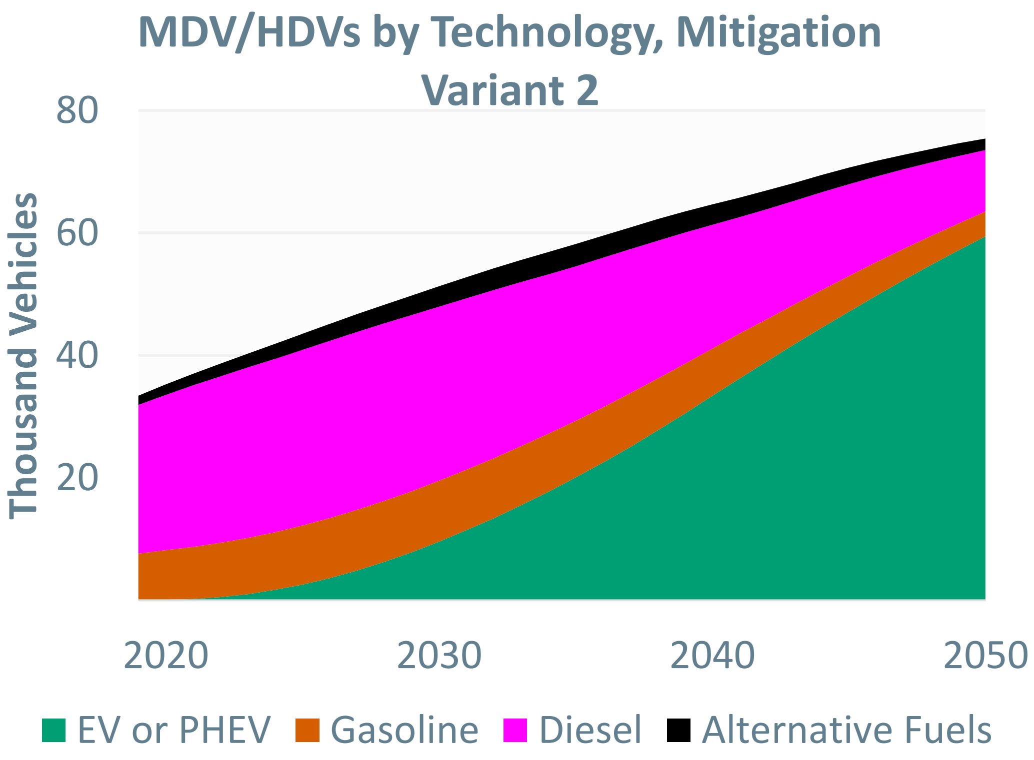
Detail: Medium- and Heavy-Duty Vehicles by Technology



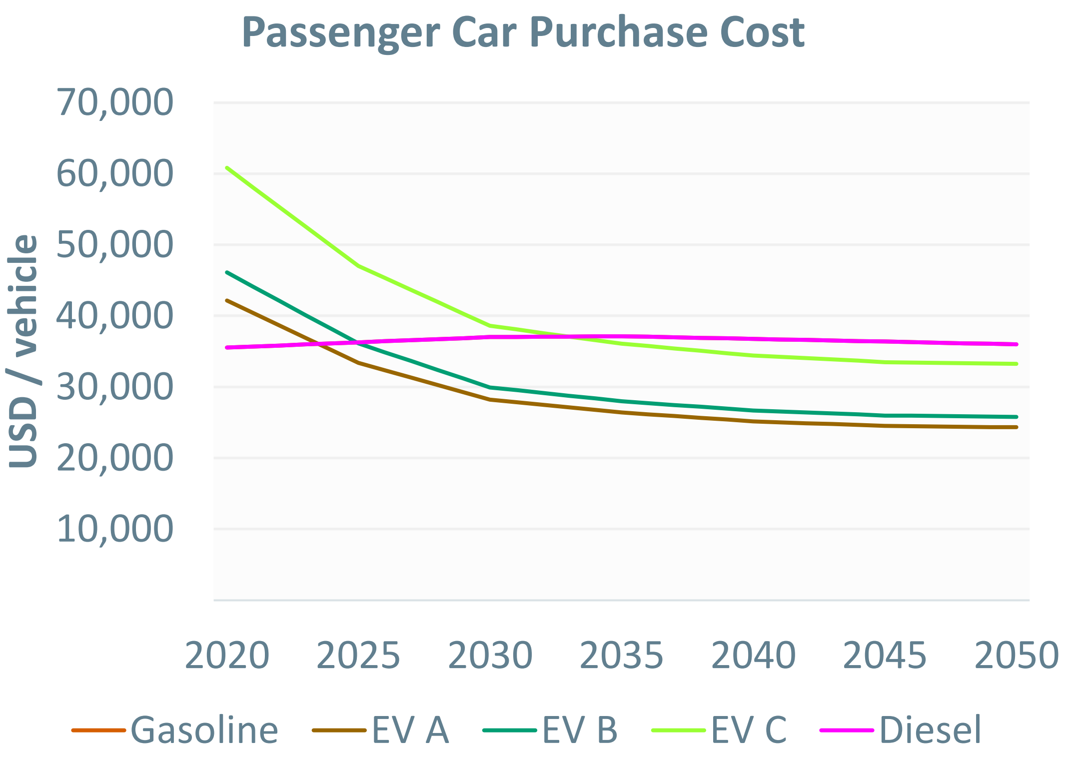


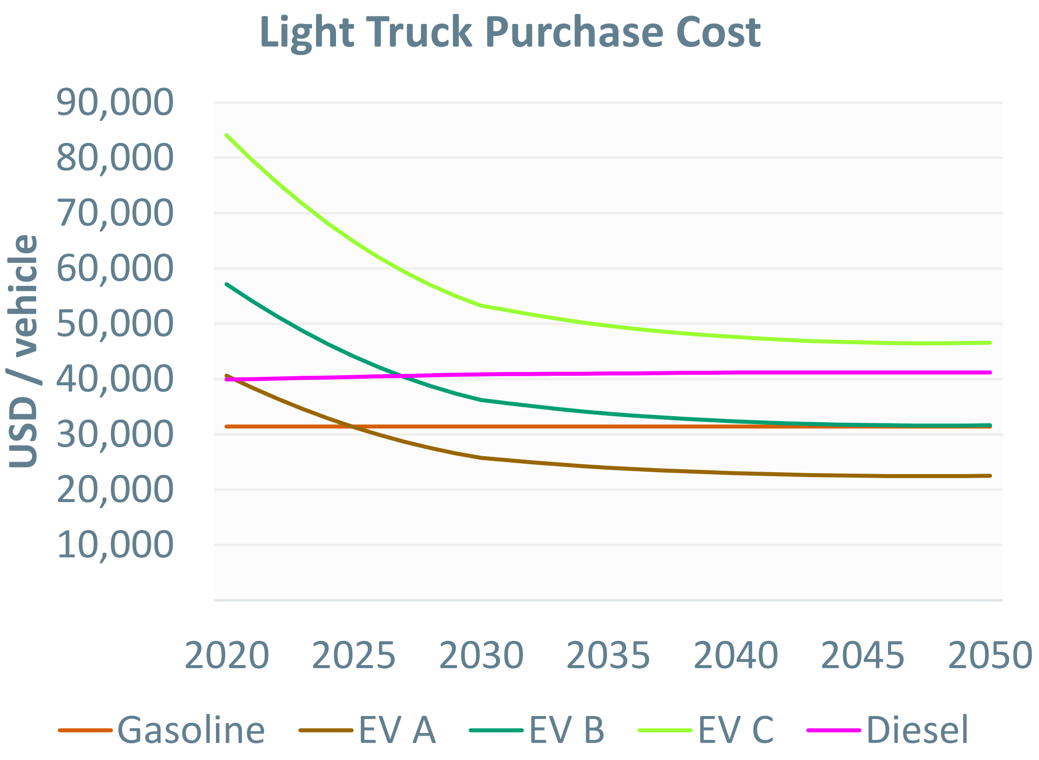
Detail: Medium- and Heavy-Duty Vehicles by Technology





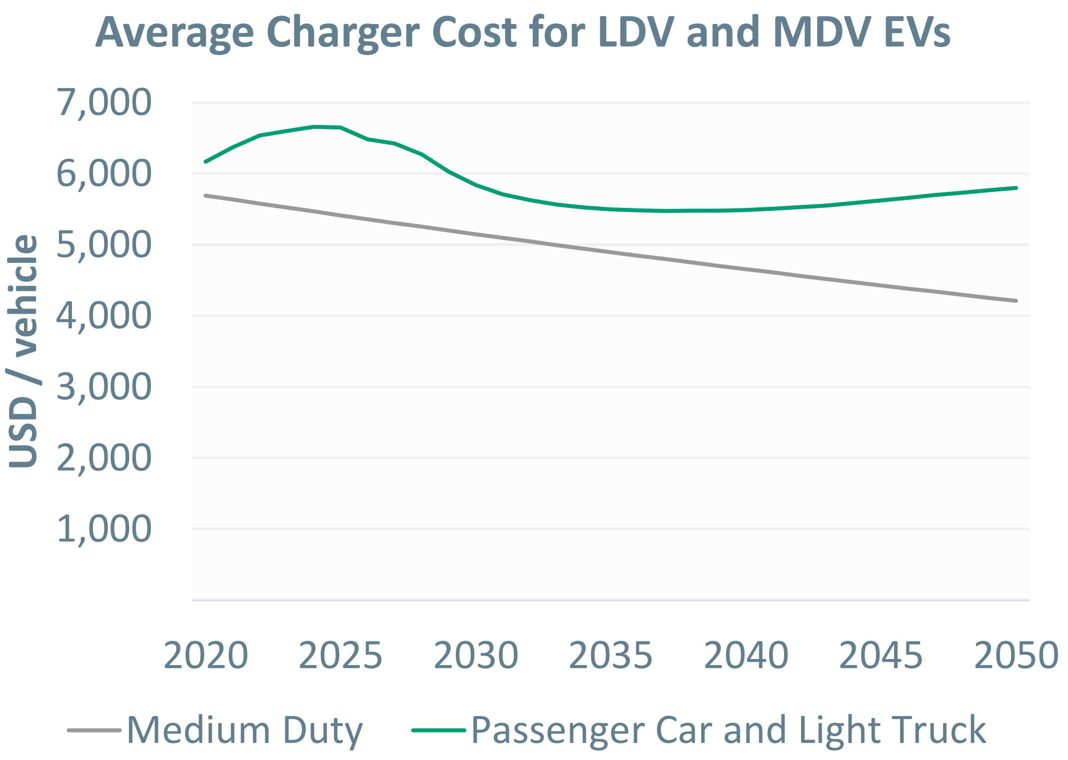
Detail: Example Light-Duty Vehicle Costs





* Only a selection of vehicle technologies are presented here, for light-duty cars and trucks only. Vehicle costs from VISION 2020 and Cadmus.

EV Charging Costs



Costs per vehicle from Cadmus, derived from cost per charger and estimated chargers per vehicle, for:

- Residential Level 1
- Residential/Public/Workplace Level 2
- Public DC fast-charger
- Medium-duty

Heavy-duty chargers assumed to cost $150k/vehicle (not shown in chart), dropping to $111k by 2050.

E15 Ethanol in Transport

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2040, ethanol blend in all motor gasoline reaches 15%-by-volume (E15)	• Ethanol constitutes 10.2%-by-volume in motor gasoline, rising to 12.1% in 2050
Performance	• Ethanol emits “biogenic” carbon dioxide, which is assigned a global warming potential (GWP) of zero	
Cost	• Ethanol for blending costs 25.1 USD/MMBTU in 2019, rising to 44.9 USD/MMBTU in 2050 • Existing equipment assumed to operate using E15 without additional cost	• Pure gasoline costs 23.8 USD/MMBTU in 2019, rising to 30.9 USD/MMBTU in 2050

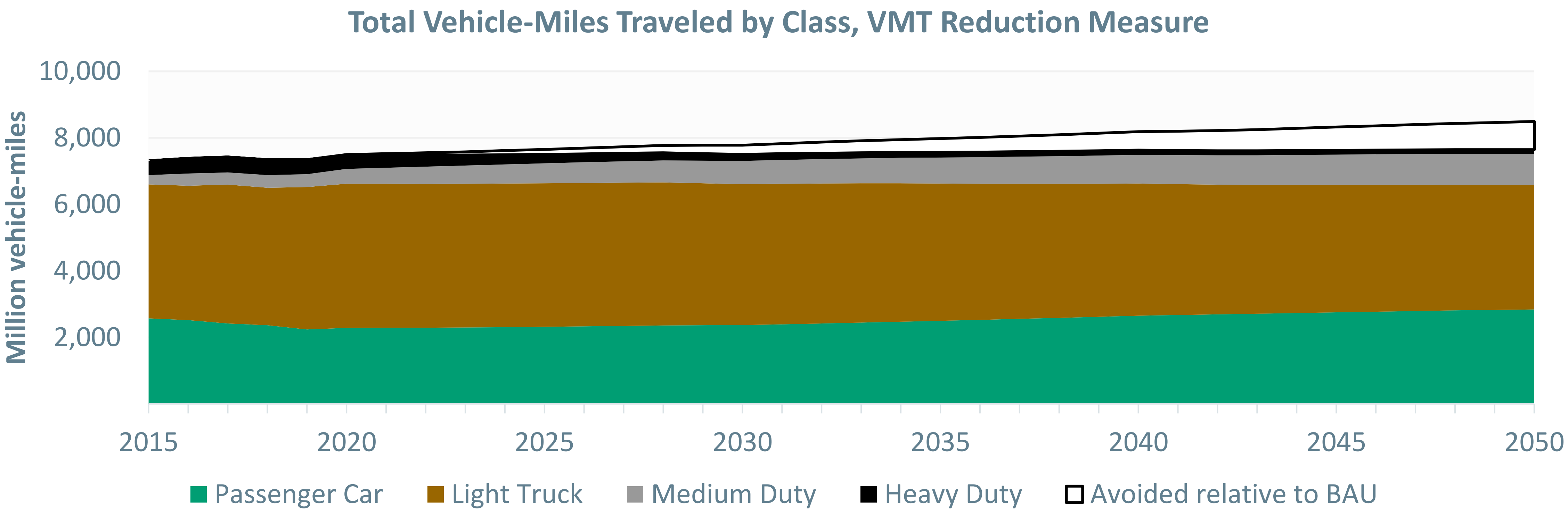
VMT Reductions

	Scenario Changes	Business-as-Usual Comparison

Saturation	• Measure encompasses urban densification, traffic demand management, active transportation and shifting to public transport
	• By 2050, annual vehicle-miles traveled (VMT) are reduced by 10% across all vehicle classes and technologies
		• Annual mileage for each weight class is:
		  • 13,852 for passenger cars
		  • 15,300 for light trucks
		  • 22,451-36,829 for MDVs
		  • 21,016-98,228 for HDVs

Performance	• No change to vehicle performance per mile traveled	
Cost	• 10% VMT reductions assumed to be achievable for $250 million USD/year	

Detail: VMT Reductions



B20 Biodiesel and Heating Oil

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2050, biodiesel blend in industrial and transport diesel, building heating oil reaches 20%-by-volume (B20)	• Industry and transport consume 4.0%-by-volume biodiesel blend, rising to 7.5% by 2050 • No blending within heating oil
Performance	• Biodiesel emits “biogenic” carbon dioxide, which is assigned a GWP of zero	
Cost	• Pure biodiesel costs 32.4 USD/MMBTU in 2019, rising to 42.2 USD/MMBTU in 2050 • Existing equipment assumed to operate using B20 without additional cost	• Diesel costs 24.9 USD/MMBTU in 2019, rising to 32.9 USD/MMBTU in 2050

Variant: B100 Biodiesel in Heating Oil

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2040, building heating oil reaches 100% biodiesel (B100)	• No blending within heating oil
Performance	• Biodiesel characteristics same as B20 Biodiesel and Heating Oil scenario	
Cost	• Capability to burn B100 requires upgrade cost of $1,045 per oil boiler or furnace, annualized over equipment's lifetime • Fuel costs same as B20 Biodiesel and Heating Oil scenario	• Residential oil furnaces cost of $4,125, lasting 26 years with annual maintenance of $70 • Residential oil boilers cost of $9,125, lasting 23 years with annual maintenance of $140 • Commercial oil furnaces serve 10,933 ft^2 with installed cost of $6,600, lasting 23 years with annual maintenance of $300 • Commercial oil boilers serve 22,667 ft^2 with installed cost of $31,500, lasting 25 years with annual maintenance of $2,300

Variant: B100 Biodiesel in Industry

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2040, industrial diesel consumption reaches 100% biodiesel (B100)	• Industry consumes 4.0%-by-volume biodiesel blend, rising to 7.5% by 2050
Performance	• Biodiesel characteristics same as B20 Biodiesel and Heating Oil scenario	
Cost	• Fuel costs same as B20 Biodiesel and Heating Oil scenario • No additional costs are included	

Variant: B100 Biodiesel in Heavy Transport

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2040, diesel consumption for heavy-duty road transport reaches 100% biodiesel (B100)	• Transport consumes 4.0%-by-volume biodiesel blend, rising to 7.5% by 2050
Performance	• Biodiesel characteristics same as B20 Biodiesel and Heating Oil scenario	
Cost	• Capability to burn B100 costs $15,000 more per vehicle • Fuel costs same as B20 Biodiesel and Heating Oil scenario	• Existing equipment assumed to operate using limited biodiesel blends without additional cost

Sustainable Aviation Fuel

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2050, drop-in biofuels displace 50% of jet kerosene	• No drop-in biofuels - jet kerosene meets 96% of aviation energy demand (remainder is aviation gasoline for small engines)
Performance	• Aviation biofuel emits “biogenic” carbon dioxide, which is assigned a GWP of zero	
Cost	• Drop-in aviation biofuel costs 37.3 USD/MMBTU • Existing aircraft assumed to operate using drop-in fuels without additional cost	• Jet kerosene costs 15.4 USD/MMBTU in 2019, rising to 22.5 USD/MMBTU in 2050

Renewable Gas in Industry

	Scenario Changes	Business-as-Usual Comparison
Saturation	• 10%/20%/80% of (fossil) natural gas consumed for industrial uses is displaced by renewable natural gas (RNG) or biogas by 2025/2030/2050, respectively	• Renewable natural gas not consumed in industry
Performance	• RNG emits "biogenic" carbon dioxide, which is assigned a GWP of zero	
Cost	• RNG costs 30 USD/MMBTU • Existing equipment assumed to operate using RNG without equipment additional cost	• Natural gas costs 7.63 USD/MMBTU in 2019, rising to 9.43 USD/MMBTU in 2050

Renewable Gas in Buildings

<table>
<tr><th></th><th>Scenario Changes</th><th>Business-as-Usual Comparison</th></tr>
<tr><td>Saturation</td><td>• Variant 1: 5%/15%/25% of (fossil) natural gas consumed for residential and commercial building uses is displaced by renewable natural gas (RNG) by 2025/2030/2050, respectively
• Variant 2: 10%/20%/80% of (fossil) natural gas consumed for residential and commercial building uses is displaced by RNG by 2025/2030/2050, respectively</td><td>• Renewable natural gas not consumed in buildings</td></tr>
<tr><td>Performance</td><td colspan="2">• RNG emits “biogenic” carbon dioxide, which is assigned a GWP of zero</td></tr>
<tr><td>Cost</td><td>• RNG costs 30 USD/MMBTU
• Existing equipment assumed to operate using RNG without additional cost</td><td>• Natural gas costs 7.63 USD/MMBTU in 2019, rising to 9.43 USD/MMBTU in 2050</td></tr>
</table>

Renewable Electricity

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** From 2032 to 2041, Renewable Energy Standard increases to 100%, affecting the mix of capacity (MW) and energy (MWh) • Existing Hydro-Quebec import contract is renewed after 2038 • **Variant 2:** Over twice as much behind-the-meter solar capacity as Variant 1	• Vermont's existing Renewable Energy Standard is met in each year, reaching 75% by 2032 (no change thereafter) • Existing Hydro-Quebec import contract ends after 2038
Performance	• Average electric production efficiency, emissions intensity is calculated internally within the model based on performance characteristics of each electric generation technology	
Cost	• Cost is calculated internally within the model based on capital, operation & maintenance and fuel cost assumptions for electric generation technologies	

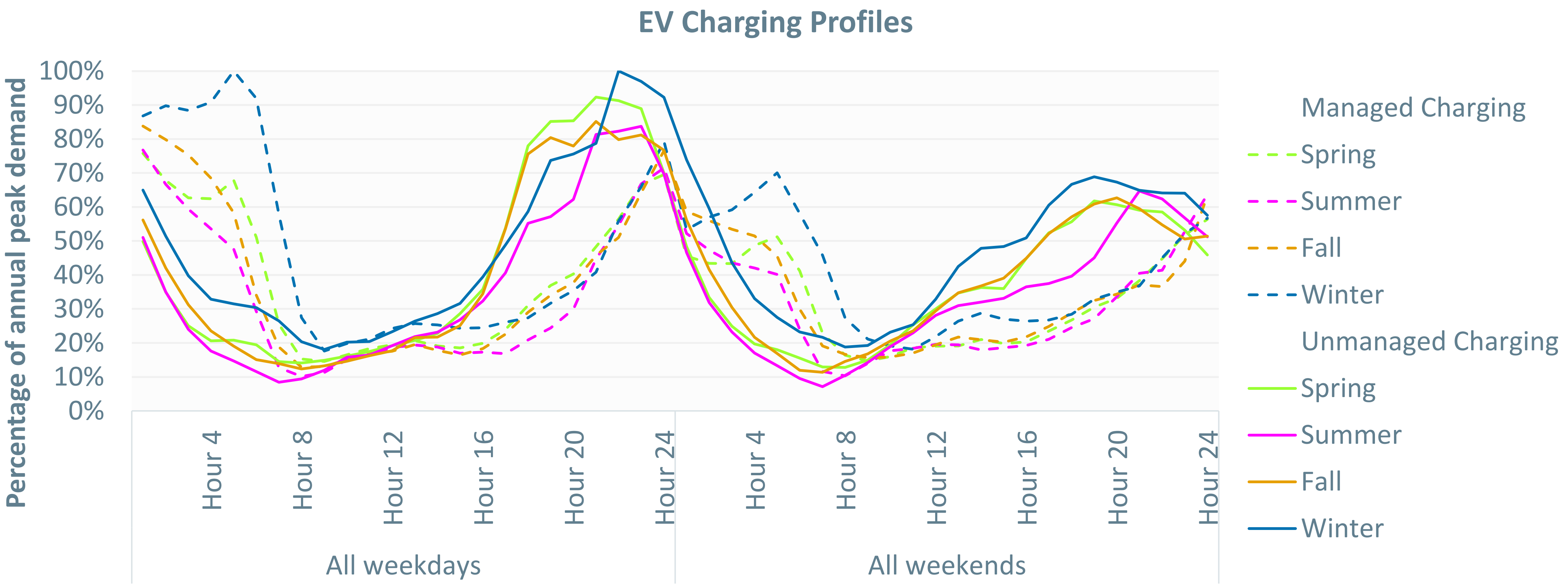
Reduced Hydro-Quebec Imports

	Scenario Changes	Business-as-Usual Comparison
Saturation	• Hydro-Quebec import contract ends in 2030	• Existing Hydro-Quebec import contract ends after 2038
Performance	• Vermont imports 1.22 TWh/year from Hydro-Quebec until 2030 • Any other Hydro-Quebec energy in New England after 2030 is counted as part of the remainder of ISO-NE system mix	• Vermont imports 1.22 TWh/year from Hydro-Quebec until 2038 • Electricity from Hydro-Quebec is eligible to meet Vermont’s Renewable Energy Standard
Cost	• Cost is calculated internally within the model based on capital, operation & maintenance and fuel cost assumptions for electric generation technologies without Hydro-Quebec	• Imported electricity assumed to cost $40/MWh

Managed EV Charging

	Scenario Changes	Business-as-Usual Comparison
Saturation	• **Variant 1:** By 2040, 50% of all electric vehicles (including PHEVs) are charged slowly while plugged in, resulting in a flatter load profile • **Variant 2:** By 2040, 80% of all electric vehicles (including PHEVs) participate in managed charging	• All electric vehicles charge as fast as possible while plugged in
Performance	• Managed charging load curve from EVI-Pro Lite, peaks at 01:00 on weekdays during winter, generally with more charging occurring overnight • No other changes to EV performance	• GMP data show charging load peaks at 21:00 on weekdays during winter
Cost	• No additional costs are assumed	

Detail: EV Charging Energy Use



* Percentage of annual *energy demand* (not load) accounts for greater number of hours during weekdays, hence higher values.

Vehicle-to-Grid (V2G) Battery Storage

	Scenario Changes	Business-as-Usual Comparison
Saturation	• By 2040, 15% of light-duty mid- and high-range BEVs (generally >150 miles per charge) participate in vehicle-to-grid discharging	• No V2G
Performance	• Each participating EV treated as a 10 kW battery storing 68 kWh • 70% minimum charge maintained • Availability of V2G batteries estimated from (unmanaged) EV charging profile, indicating when vehicles are plugged in	
Cost	• Additional $5,000 per participating EV for V2G-capable charging station	

Non-Energy Sector Mitigation Options

The following reductions are included, based on estimates in each sector from state agencies and from EFG/Cadmus:

- From **agriculture**:
  - Agricultural soil carbon sequestration reaches -98,557 $MTCO_2e$/year by 2050
  - Dietary changes reduce enteric fermentation CH_4 by 20% in 2035 and 30% by 2040, compared to Business-as-Usual
  - Digesters reduce manure management CH_4 by 30% in 2030, compared to Business-as-Usual
- From **waste**:
  - SEI assumes that by 2050, 50% reduction in CH_4 is achievable from wastewater gas flaring
- From **industrial processes and product use**:
  - Emissions from ozone-depleting substances decline to 164,590 $MTCO_2e$/year by 2029, followed by continued declining trend of -4.9%/year
  - Emissions from semiconductor manufacture decline to 179,000 $MTCO_2e$/year by 2030
- No change from business-as-usual **land use, land-use change and forestry** carbon sink projection

Individual Mitigation Options

Mitigation Scenarios

Scenario Hierarchy

- Business-as-Usual
- Central Mitigation Scenario
  - Biofuel Emphasis
  - Local Electricity Resources

Mitigation scenarios combine individual measures to achieve Vermont's GWSA targets.

Year	GHG Target	Gross* GHG Target [MMTCO$_2$e/yr]
2025	26%-below-2005	7.48
2030	40%-below-1990	5.18
2050	80%-below-1990	1.73

*Gross emissions exclude the carbon sink from by land use, land-use change and forestry

Central Mitigation Scenario

Also called "CAP Mitigation Scenario" by EFG/Cadmus

Includes:

- Building Shell Improvements (variant 2)
- Clean Cooking
- Heat Pump Water Heating
- Heat Pump Residential Space Conditioning (variant 1)
- Heat Pump Commercial Space Conditioning (variant 1)
- Advanced Wood Heating (variant 1)
- Commercial District Heating
- Renewable Gas in Buildings (variant 1)
- Renewable Gas in Industry
- Phasing Out Internal Combustion Engines (variant 1)
- E15 in Transport
- B20 in Transport and Heating Oil
- VMT Reductions
- Sustainable Aviation Fuel
- B100 in Industry
- Renewable Electricity (variant 1)
- Managed EV Charging (variant 1)
- Non-energy mitigation options

Biofuel Emphasis Scenario

Includes:

- Building Shell Improvements (variant 2)
- Clean Cooking
- Heat Pump Water Heating
- Heat Pump Residential Space Conditioning (variant 2, reduced)
- Heat Pump Commercial Space Conditioning (variant 2, reduced)
- Advanced Wood Heating (variant 2, increased)
- Commercial District Heating
- Renewable Gas in Buildings (variant 2, increased)
- Renewable Gas in Industry

Green text differs from Central Mitigation Scenario

- Phasing Out Internal Combustion Engines (variant 2, reduced)
- E15 in Transport
- B100 in Heating Oil
- B100 in Heavy-Duty Transport (B20 in remaining transport)
- VMT Reductions
- Sustainable Aviation Fuel
- B100 in Industry
- Renewable Electricity (variant 1)
- Managed EV Charging (variant 1)
- Non-energy mitigation options

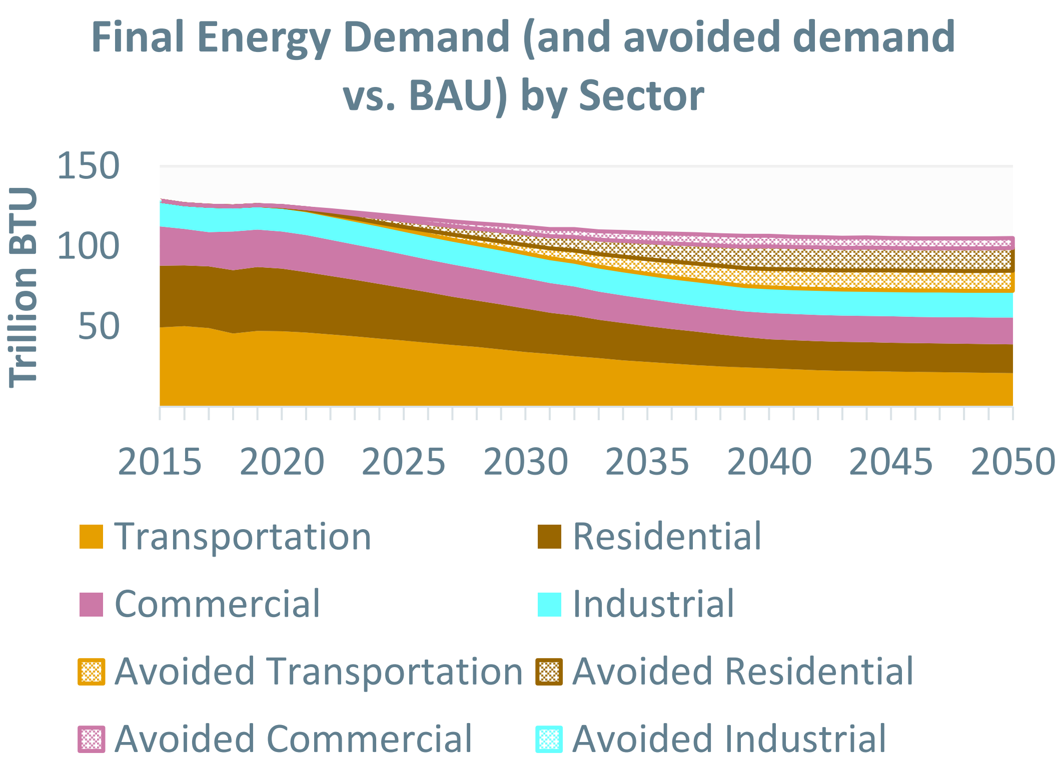
Local Electricity Resources Scenario

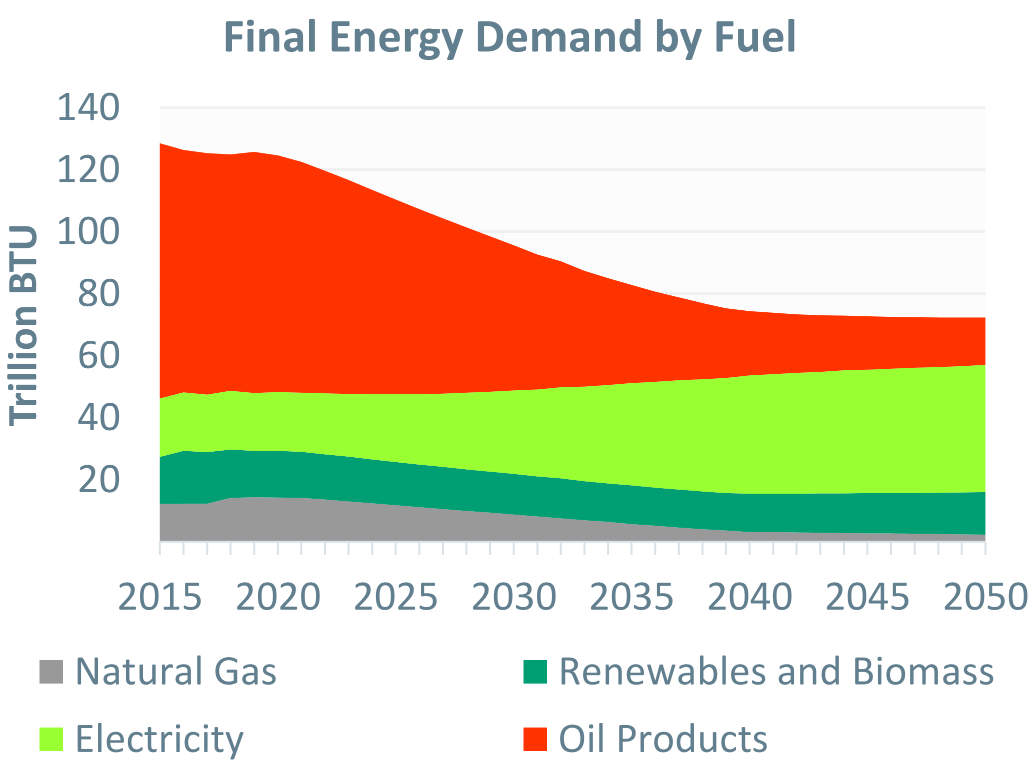
Includes:

- Building Shell Improvements (variant 2)
- Clean Cooking
- Heat Pump Water Heating
- Heat Pump Residential Space Conditioning (variant 1)
- Heat Pump Commercial Space Conditioning (variant 1)
- Advanced Wood Heating (variant 1)
- ~~Commercial District Heating~~
- Renewable Gas in Buildings (variant 1)
- Renewable Gas in Industry
- Phasing Out Internal Combustion Engines (variant 1)
- E15 in Transport
- B20 in Transport and Heating Oil
- VMT Reductions
- Sustainable Aviation Fuel
- B100 in Industry
- Renewable Electricity (variant 2, more BTM PV)
- Managed EV Charging (variant 2, increased)
- Non-energy mitigation options
- Reduced Hydro-Quebec Imports
- V2G Battery Storage

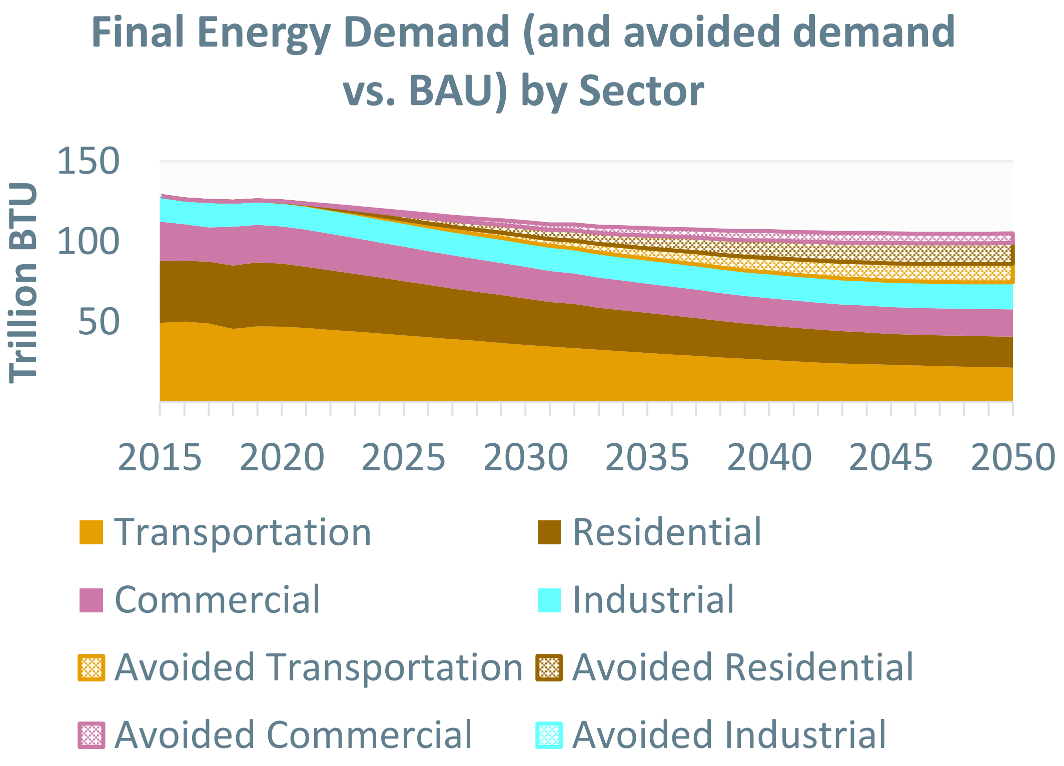
Green text differs from Central Mitigation Scenario

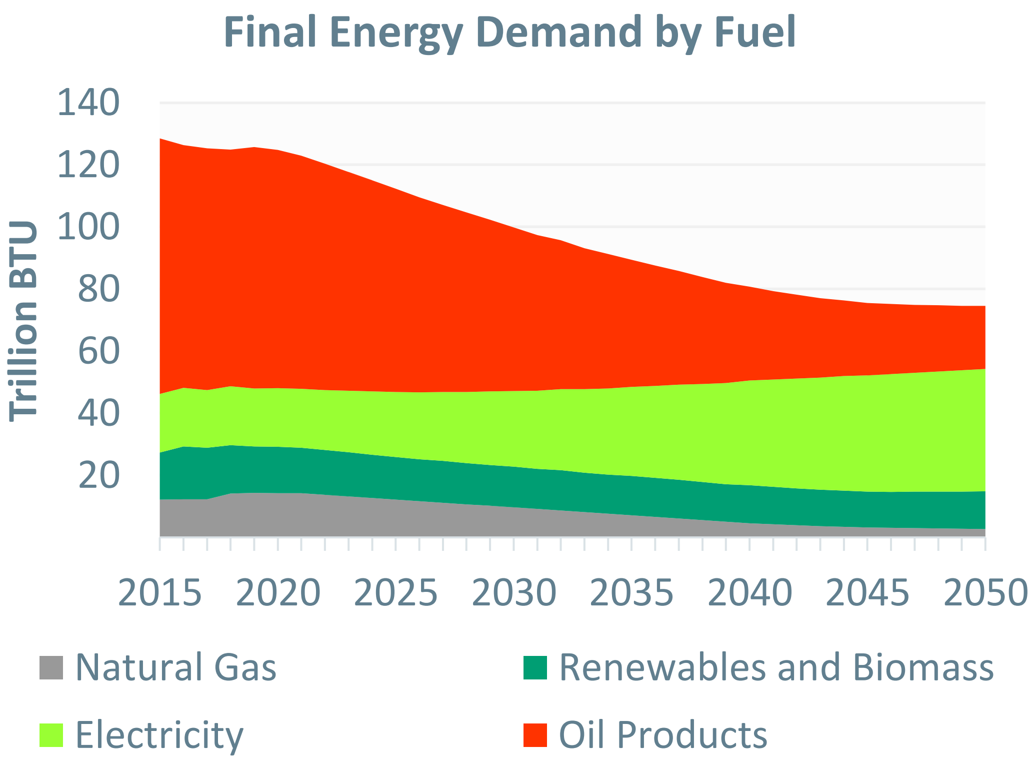
Energy Demand in Central Mitigation Scenario



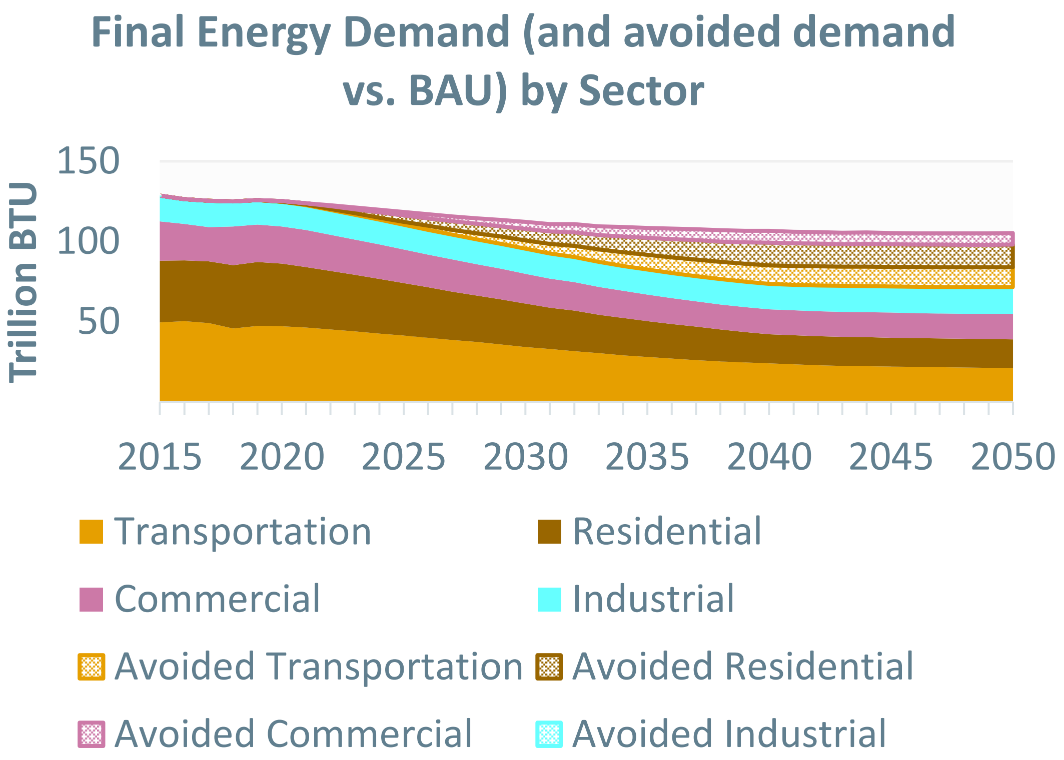


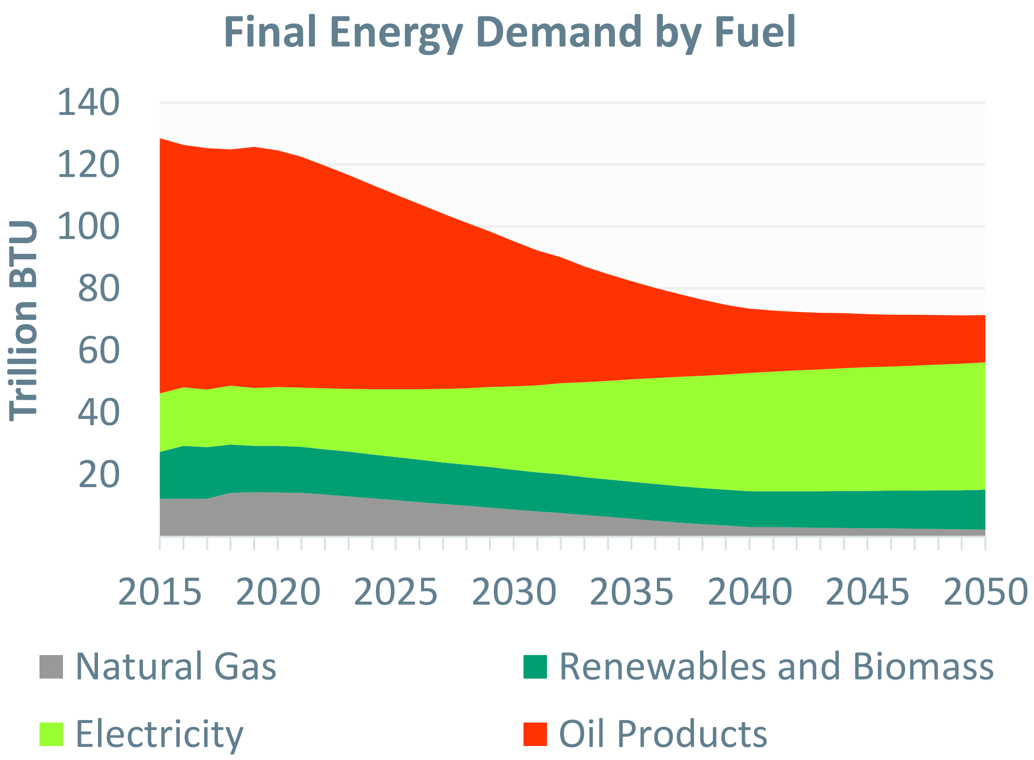
Energy Demand in Biofuel Emphasis Scenario



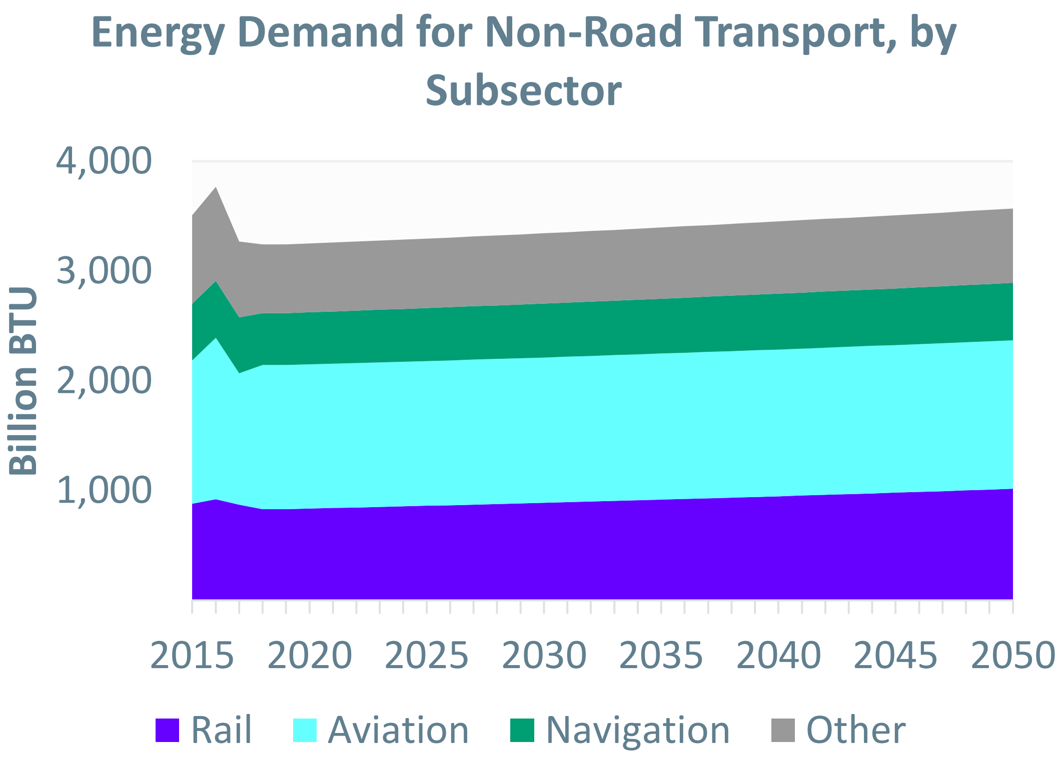


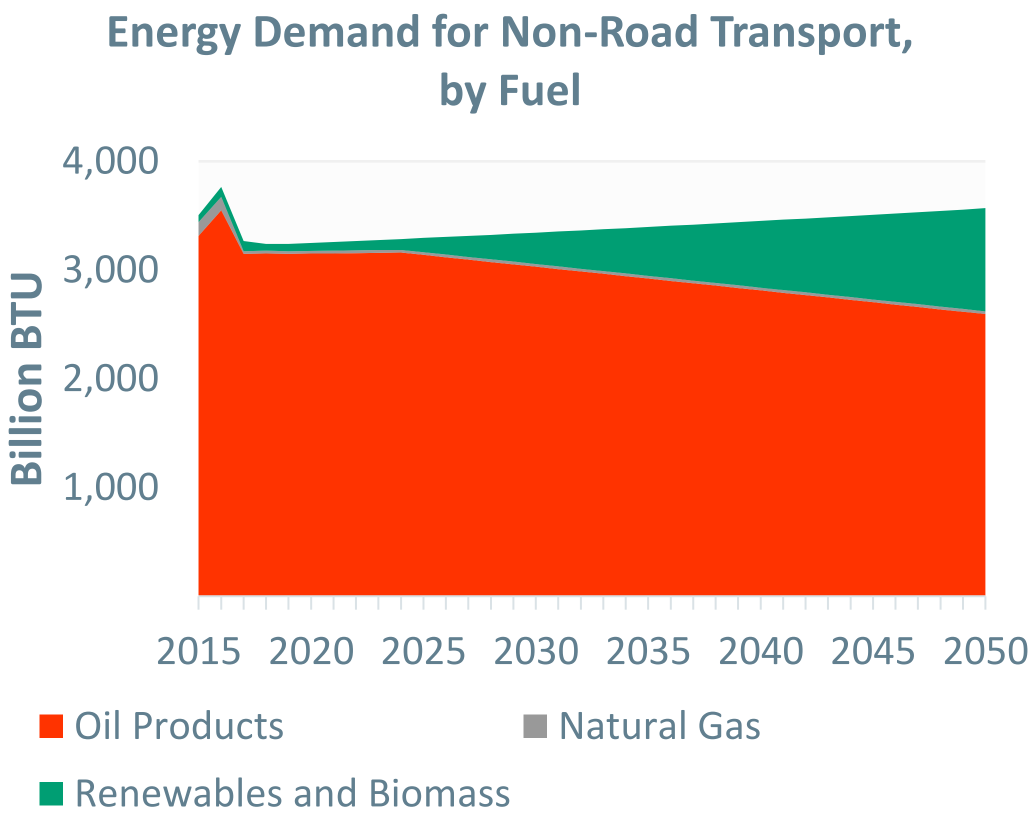
Energy Demand in Local Electricity Resources Scenario



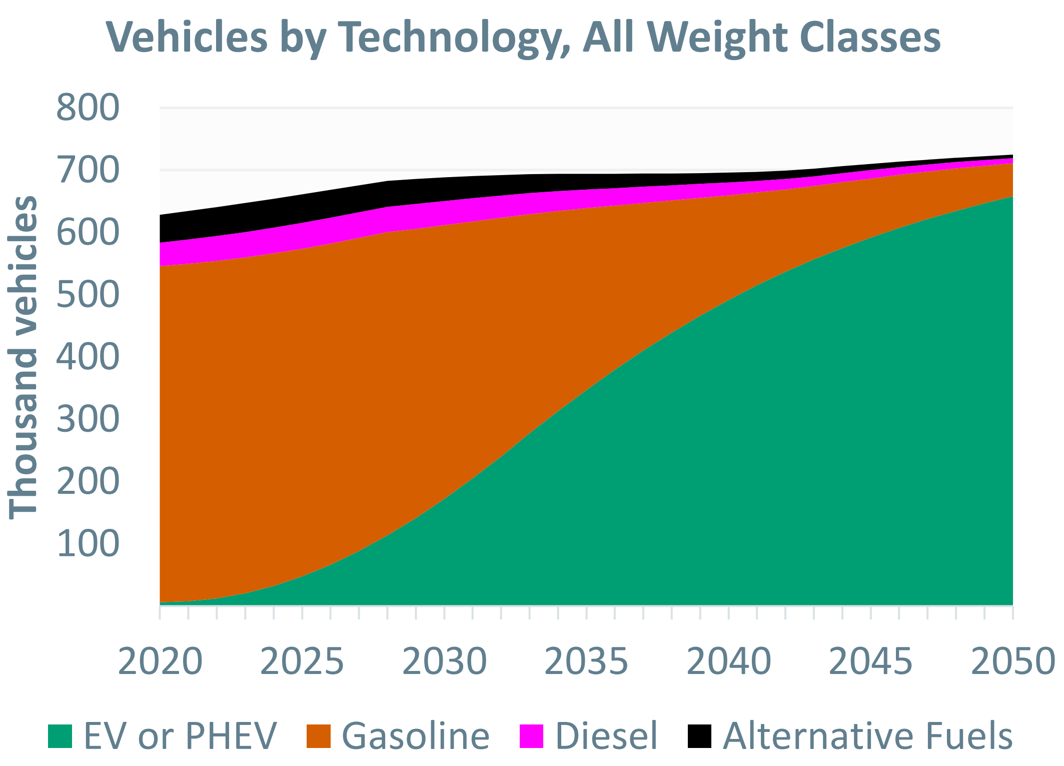


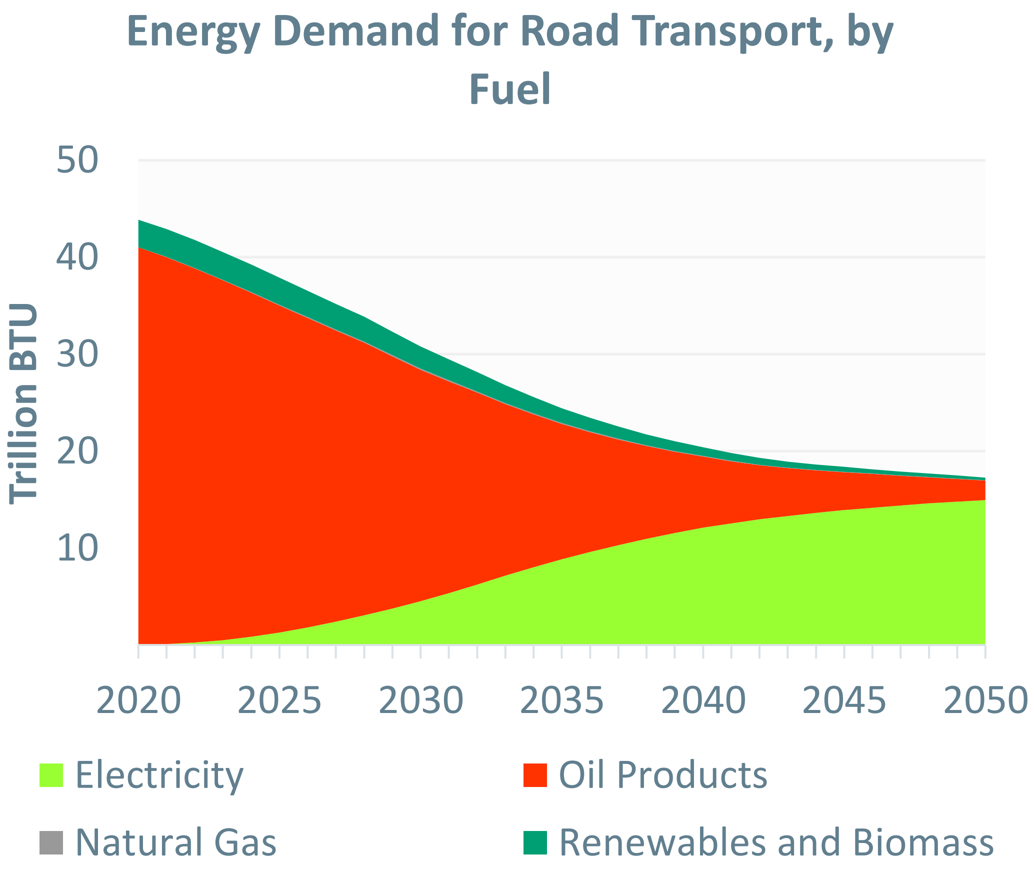
Detail: Transport Demand in Central Mitigation Scenario





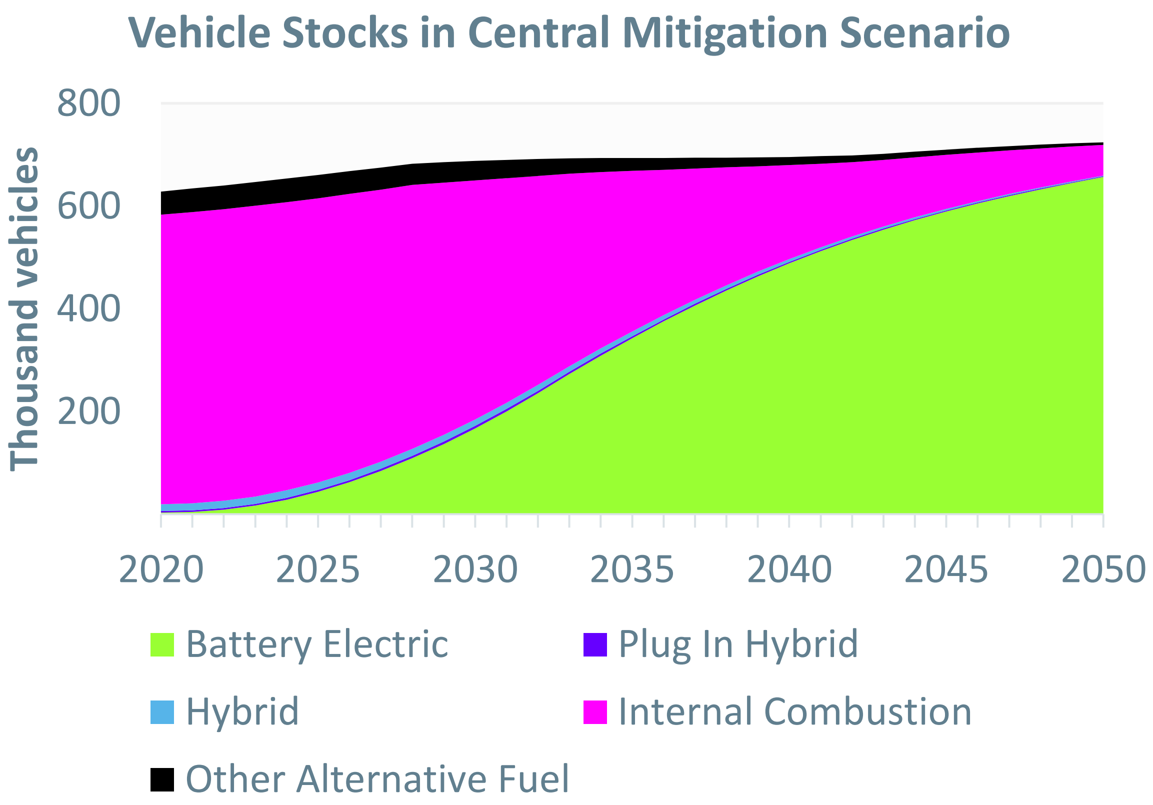
Detail: Transport Demand in Central Mitigation Scenario

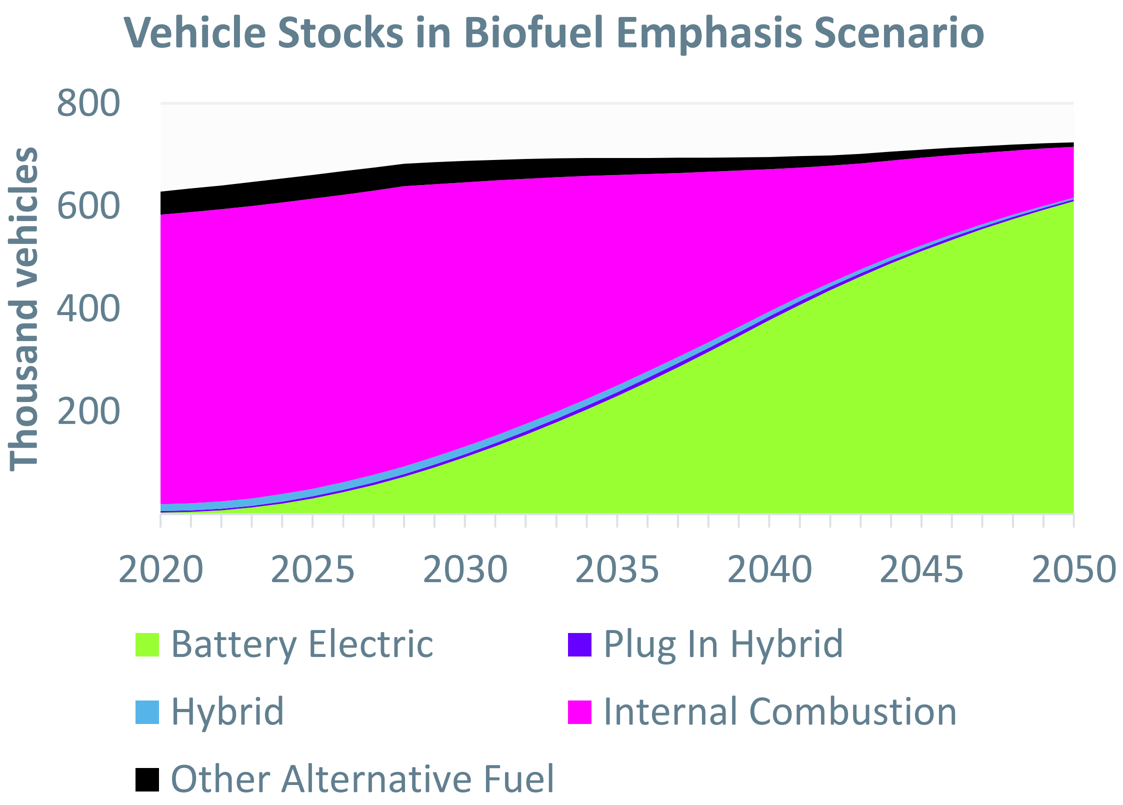




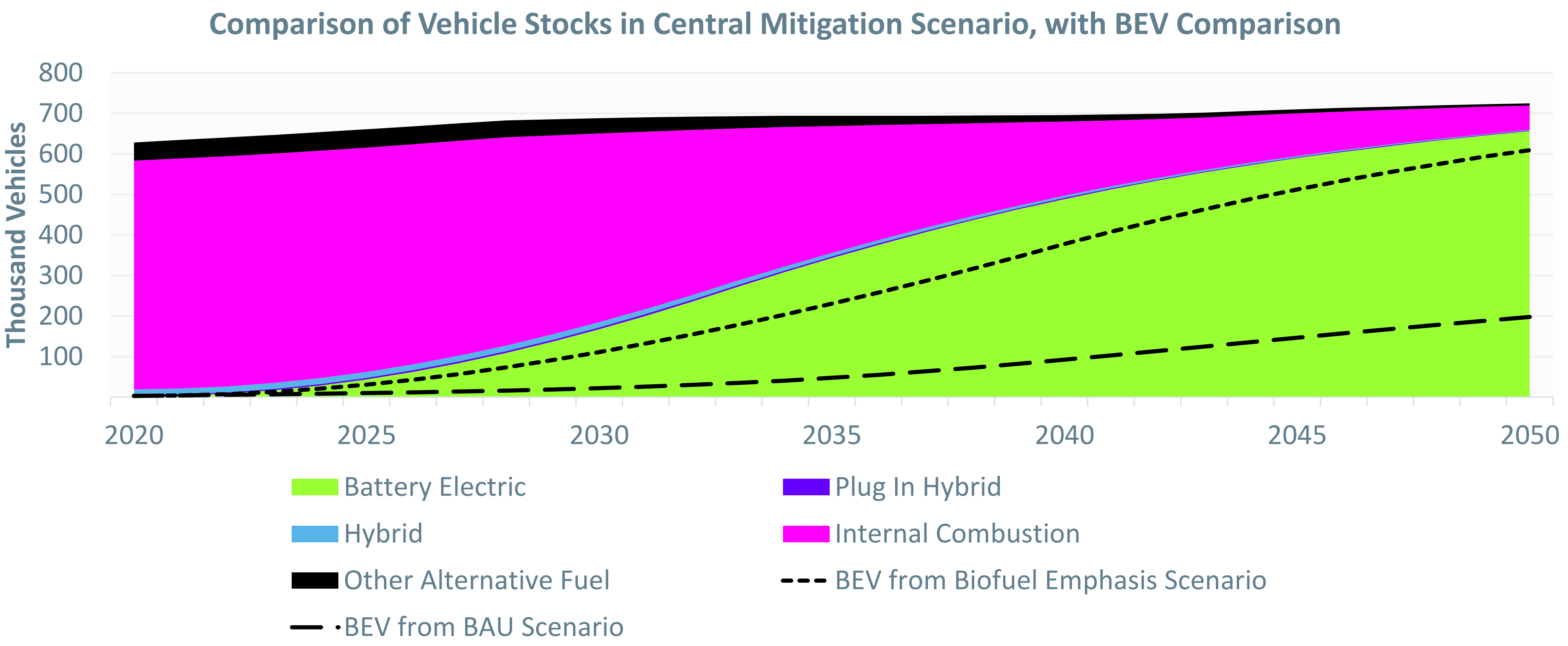
* Alternative fuels include LNG, CNG, propane, E85 and natural gas fuel cell

Detail: Vehicle Types in Two Mitigation Scenarios

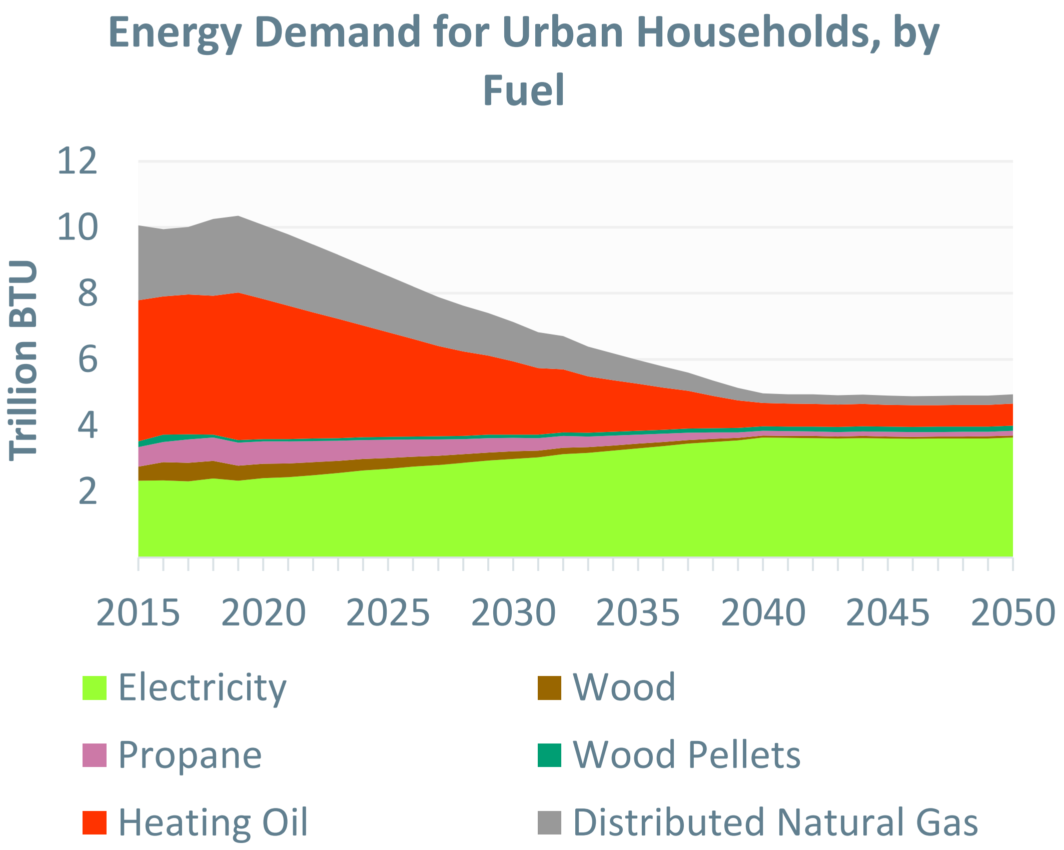


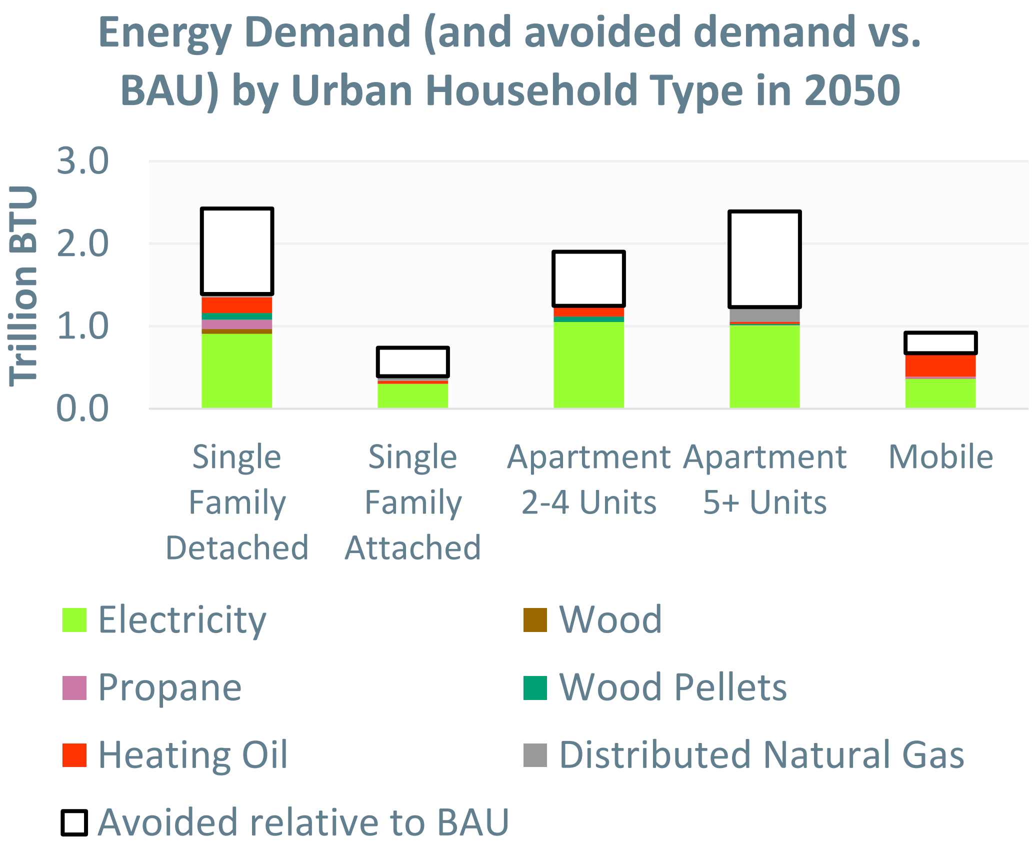


Detail: Battery Electric Vehicle Stock Comparison

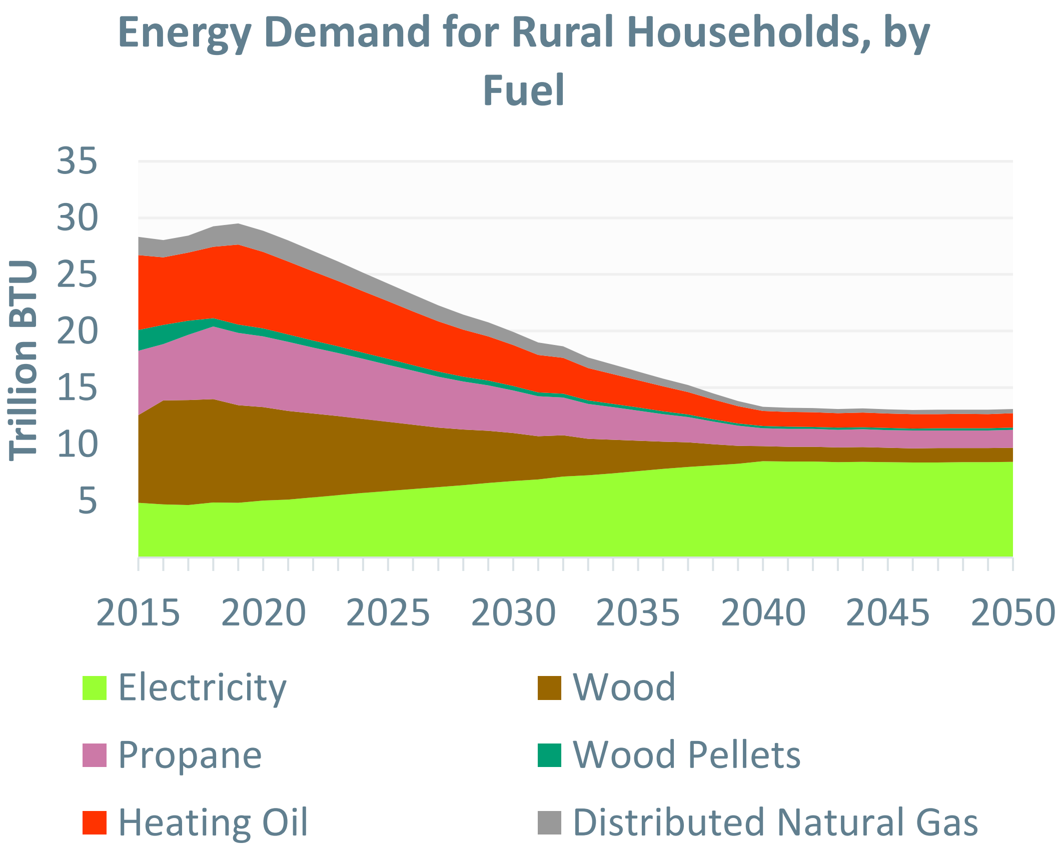


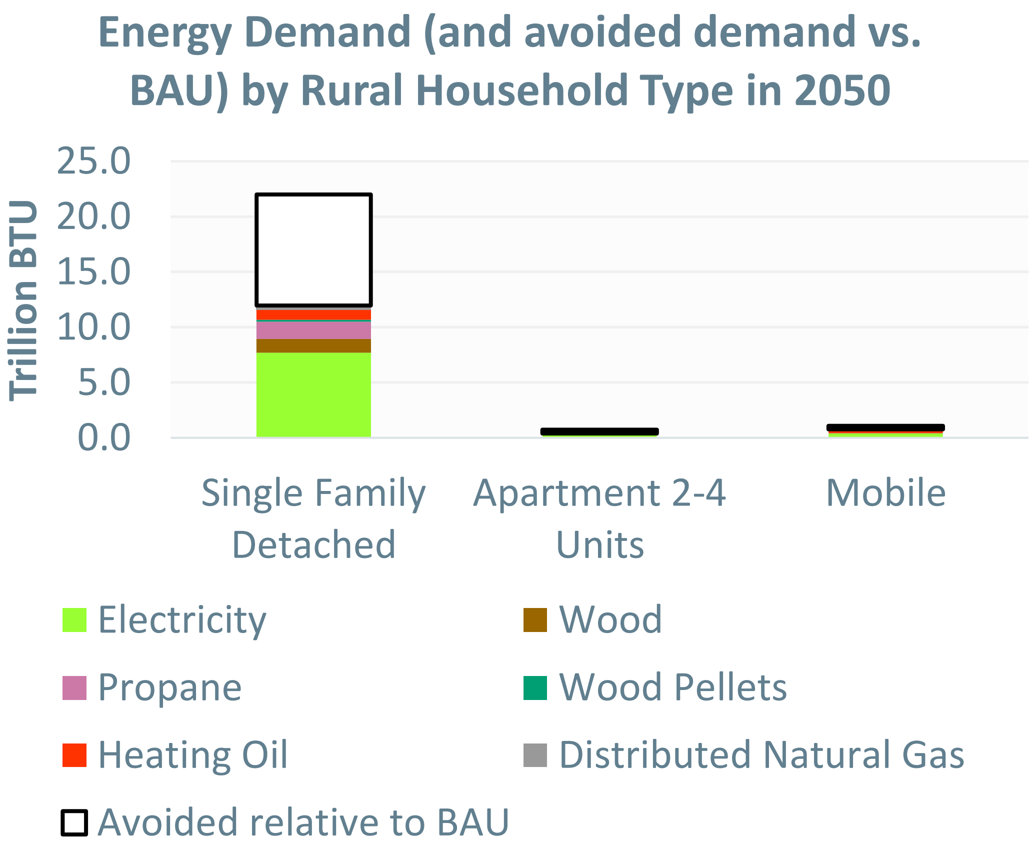
Detail: Urban Household Demand in Central Mitigation Scenario



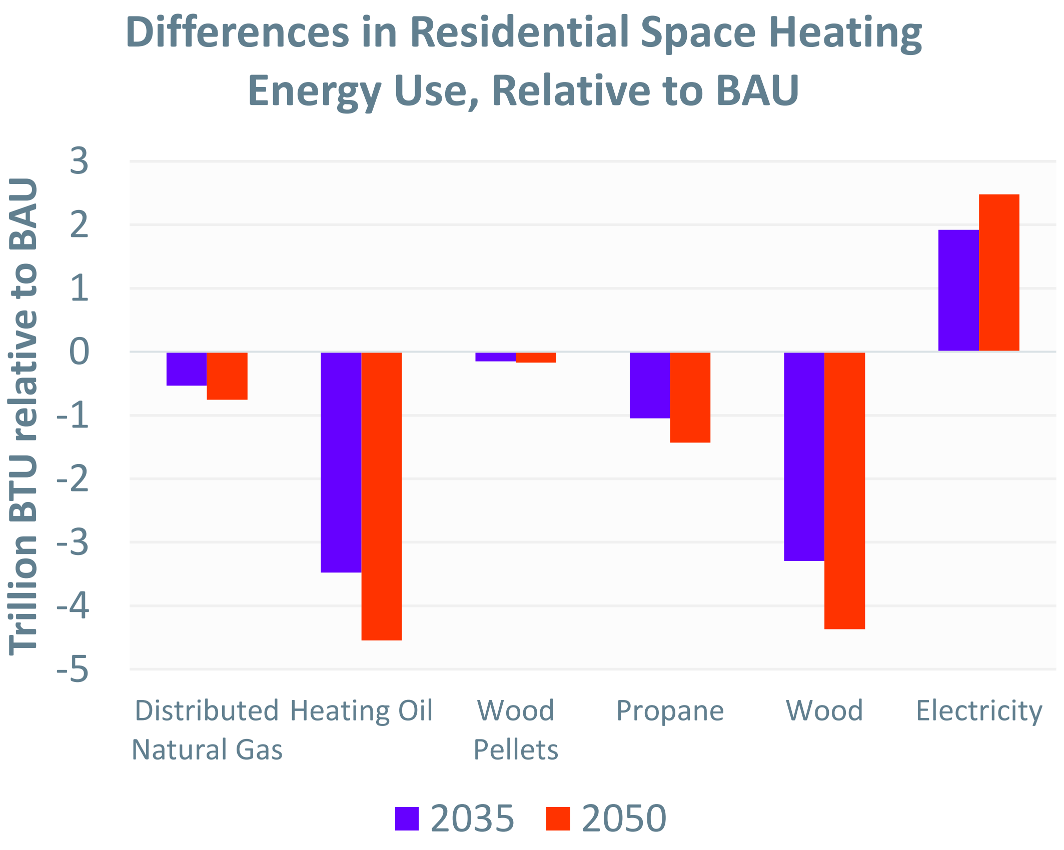


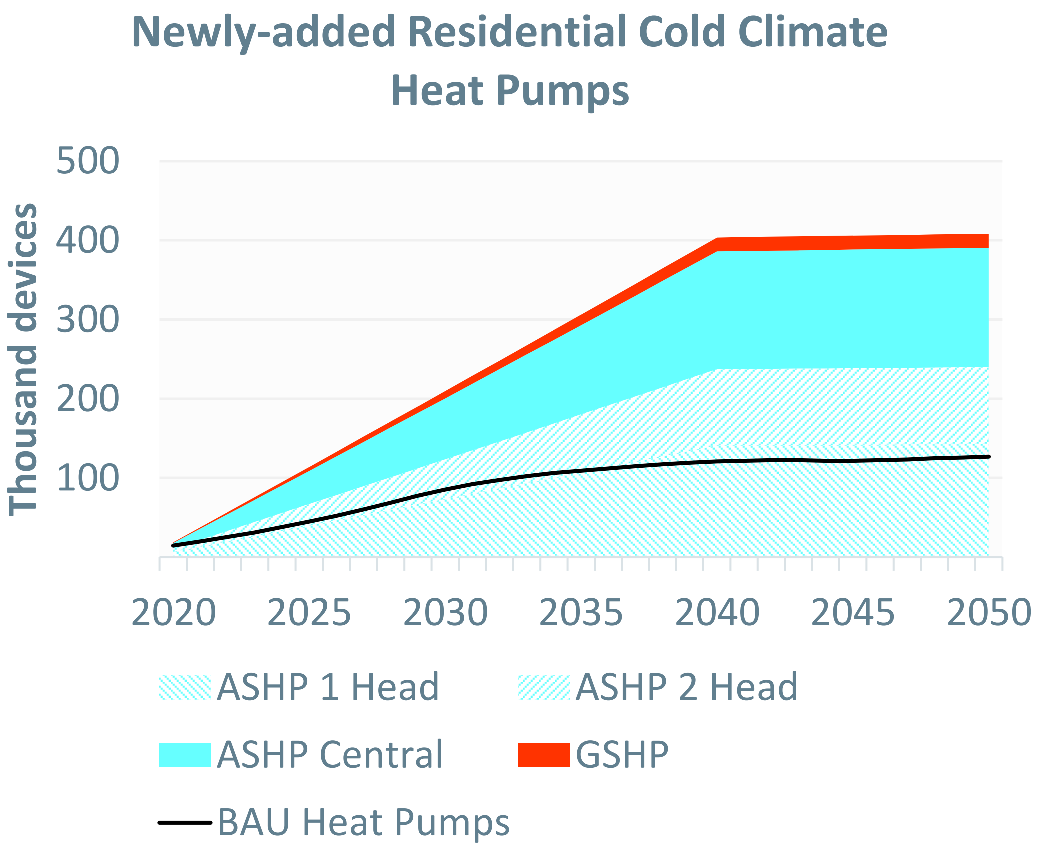
Detail: Rural Household Demand in Central Mitigation Scenario



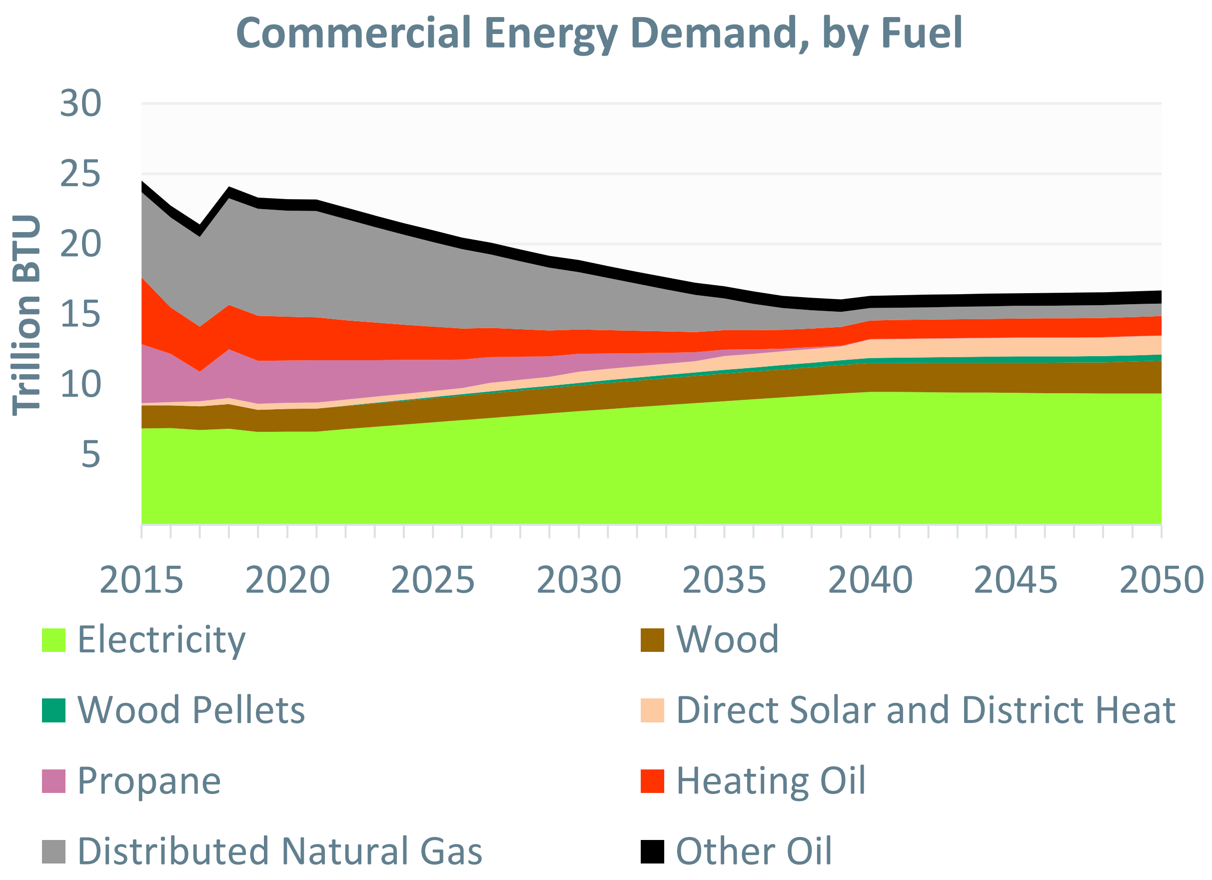


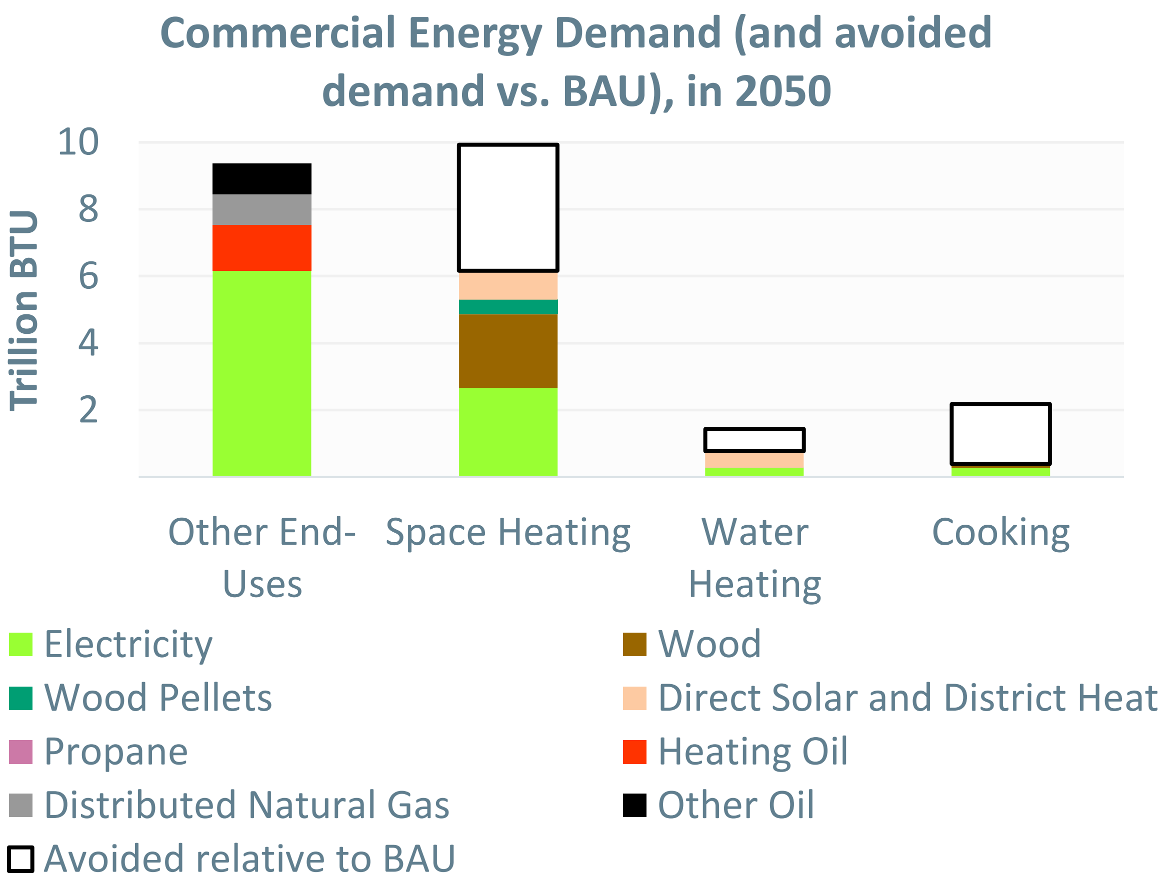
Detail: Household Space Heating Demand in Central Mitigation Scenario





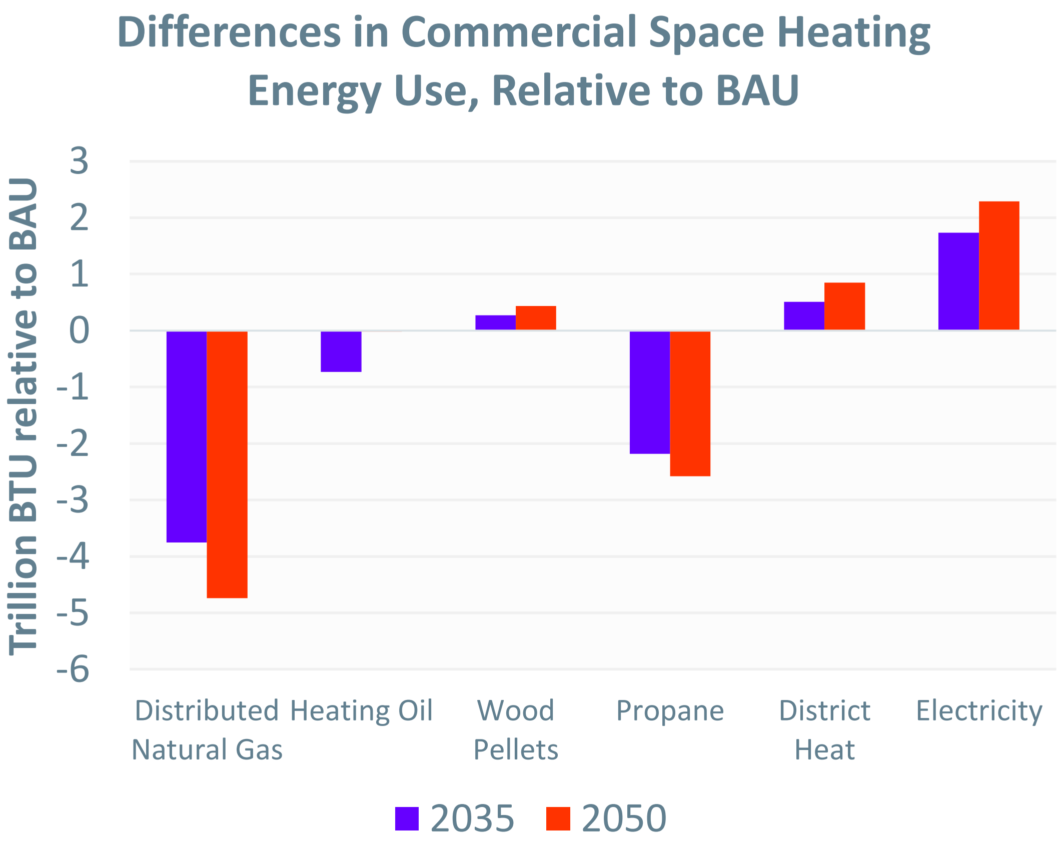
Detail: Commercial Demand in Central Mitigation Scenario

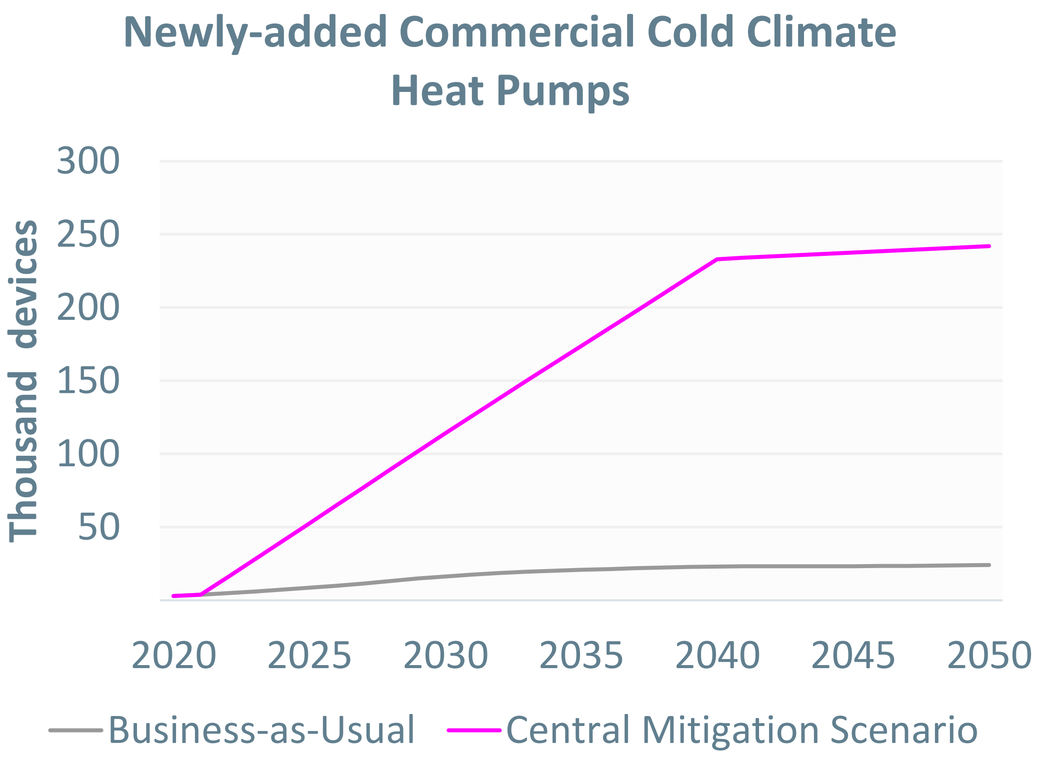




* “Other Oil”, in the context of these charts, includes ethanol blended with gasoline

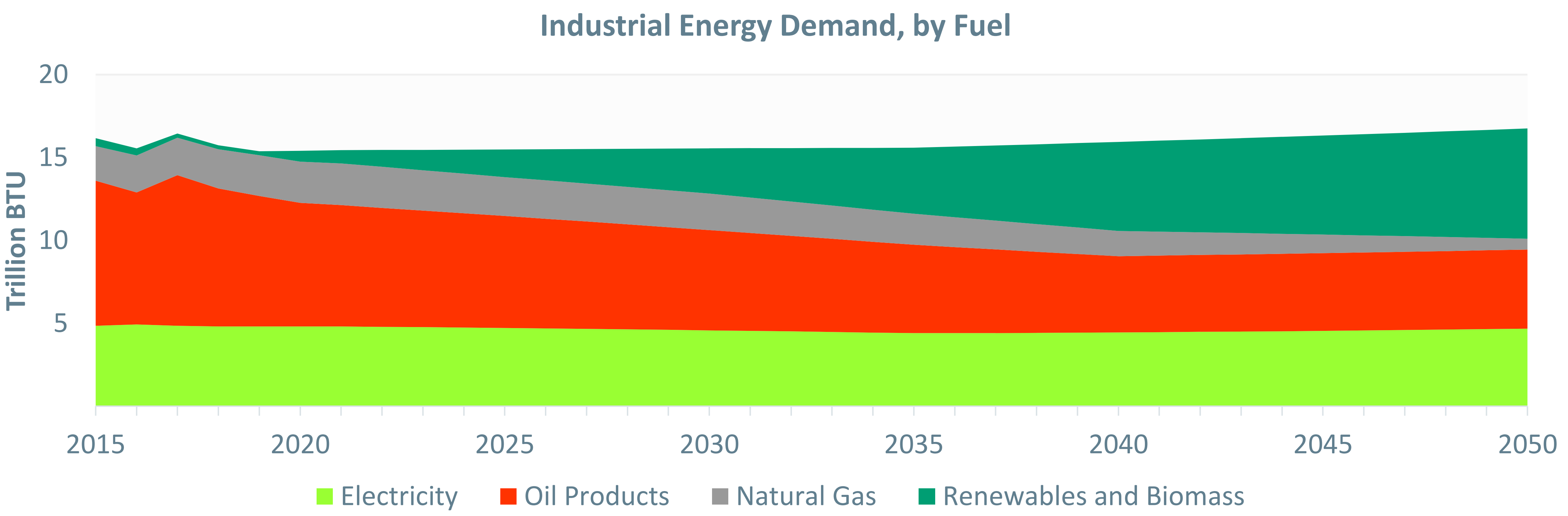
Detail: Commercial Space Heating Demand in Central Mitigation Scenario



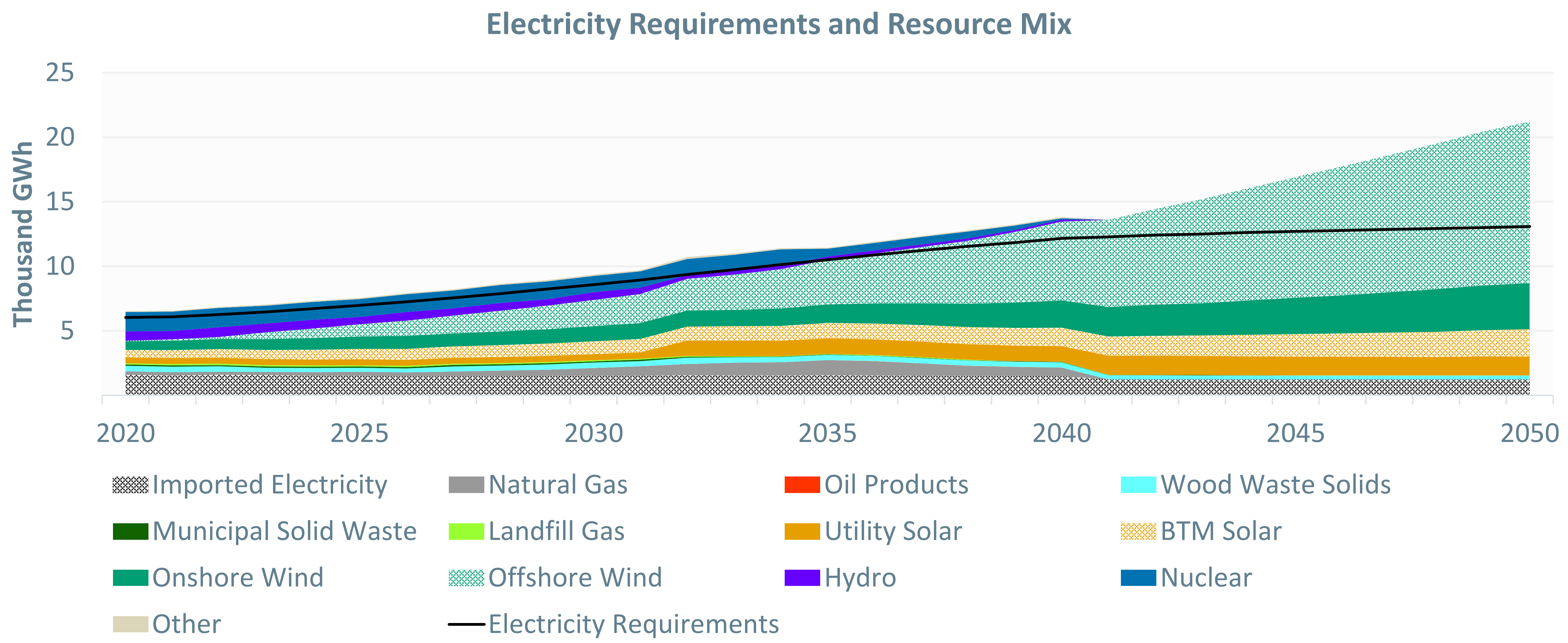


* Different heat pump technologies are not resolved in the commercial sector. One heat pump serves approximately 500 square feet of commercial space.

Detail: Industrial Demand in Central Mitigation Scenario

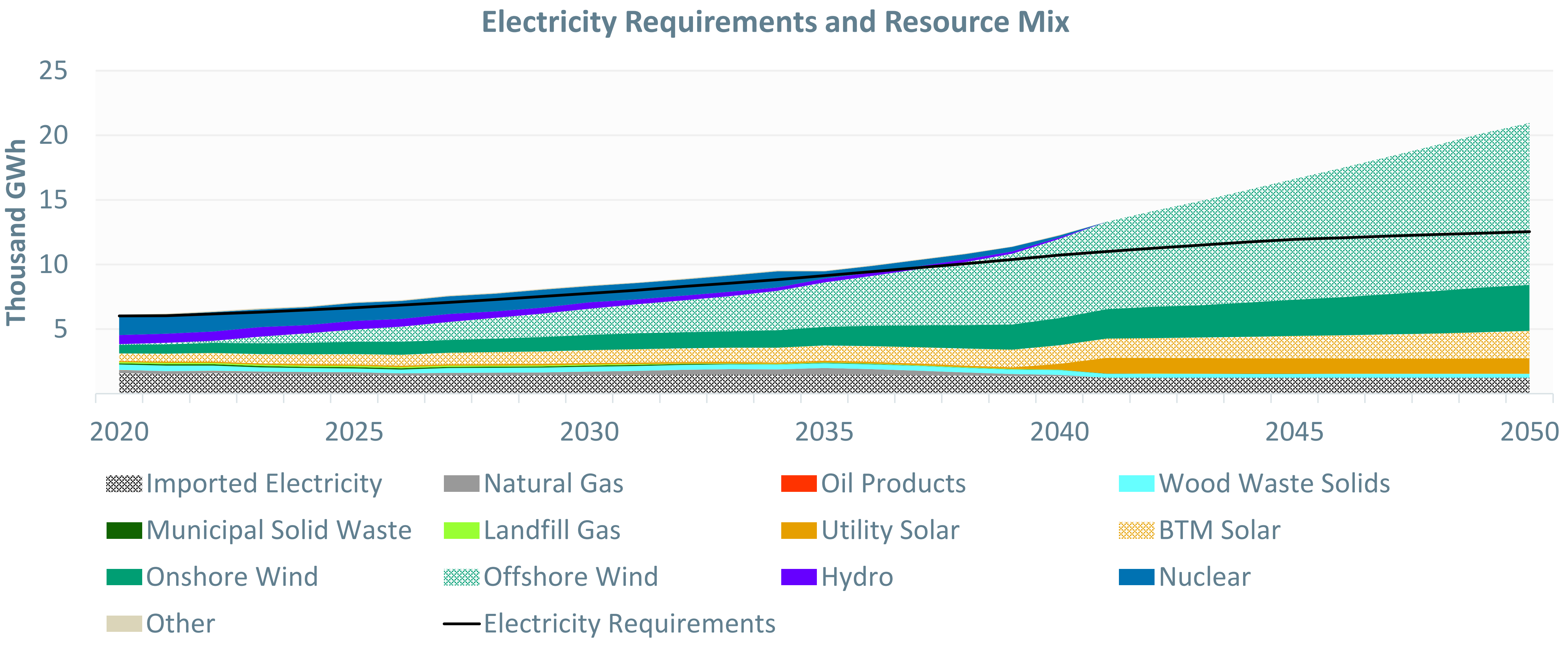


Electricity Mix in Central Mitigation Scenario

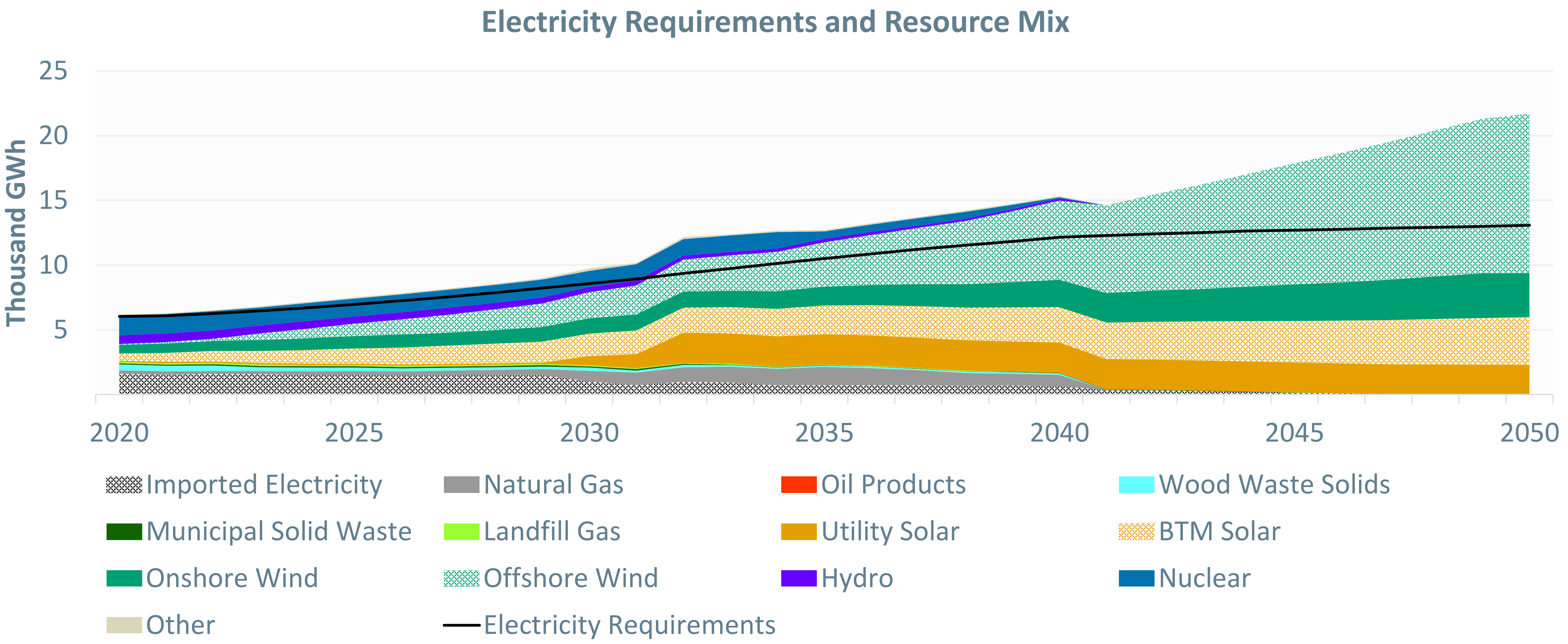


* Electricity requirements illustrate Vermont demand plus transmission and distribution loss. Additional electricity production is considered surplus – it may be exported or curtailed.

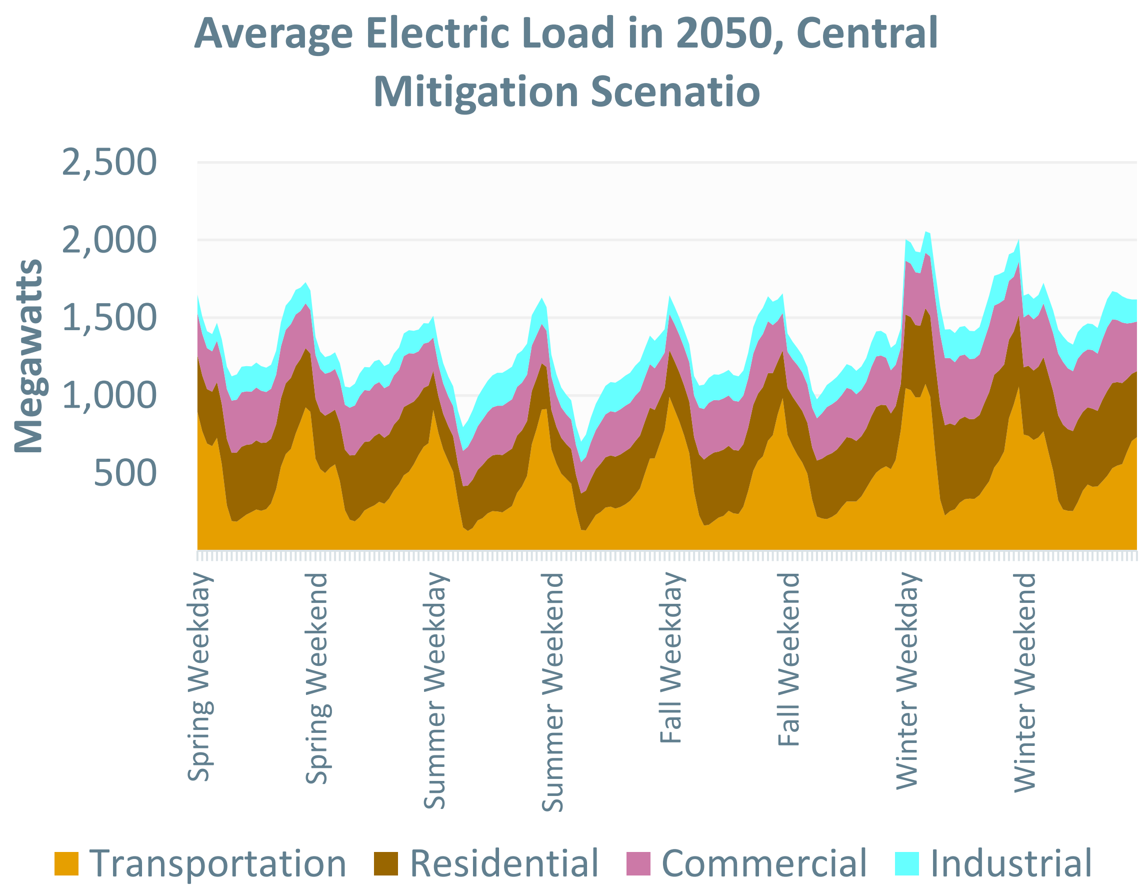
Electricity Mix in Biofuel Emphasis Scenario

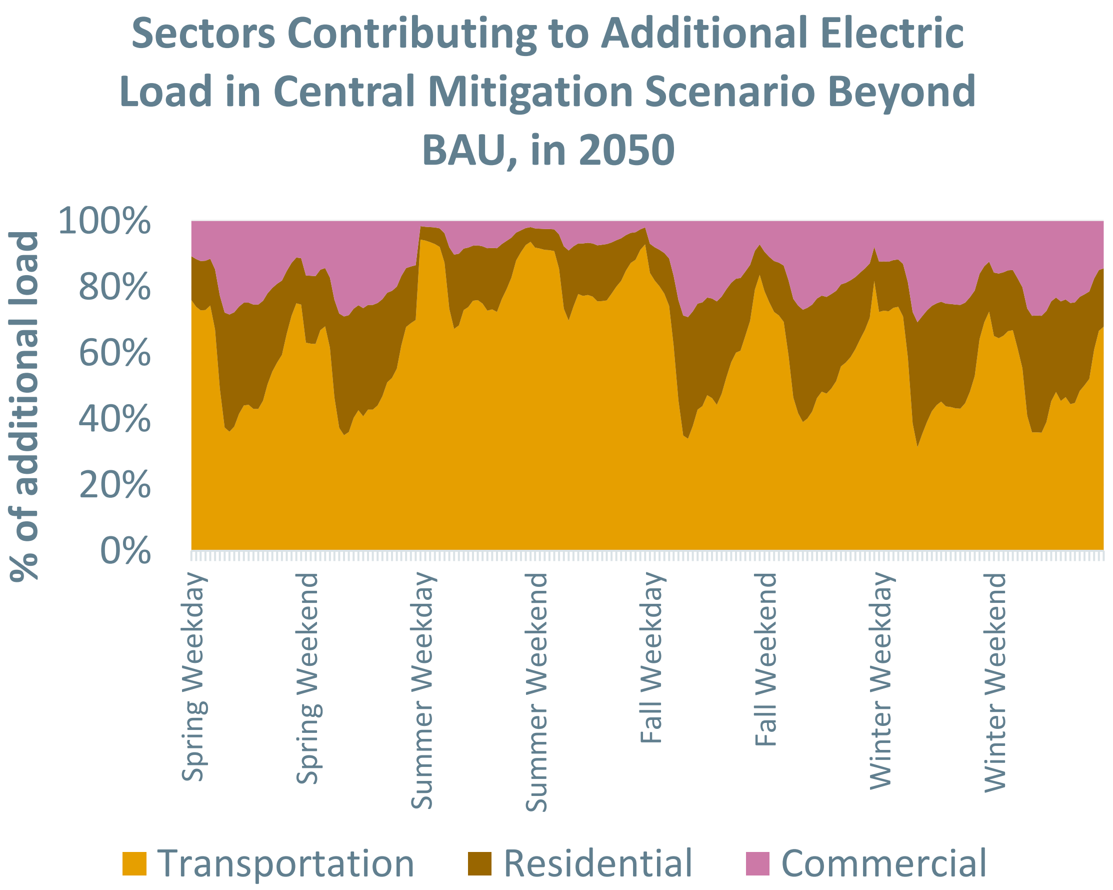


Electricity Mix in Local Electricity Resources Scenario



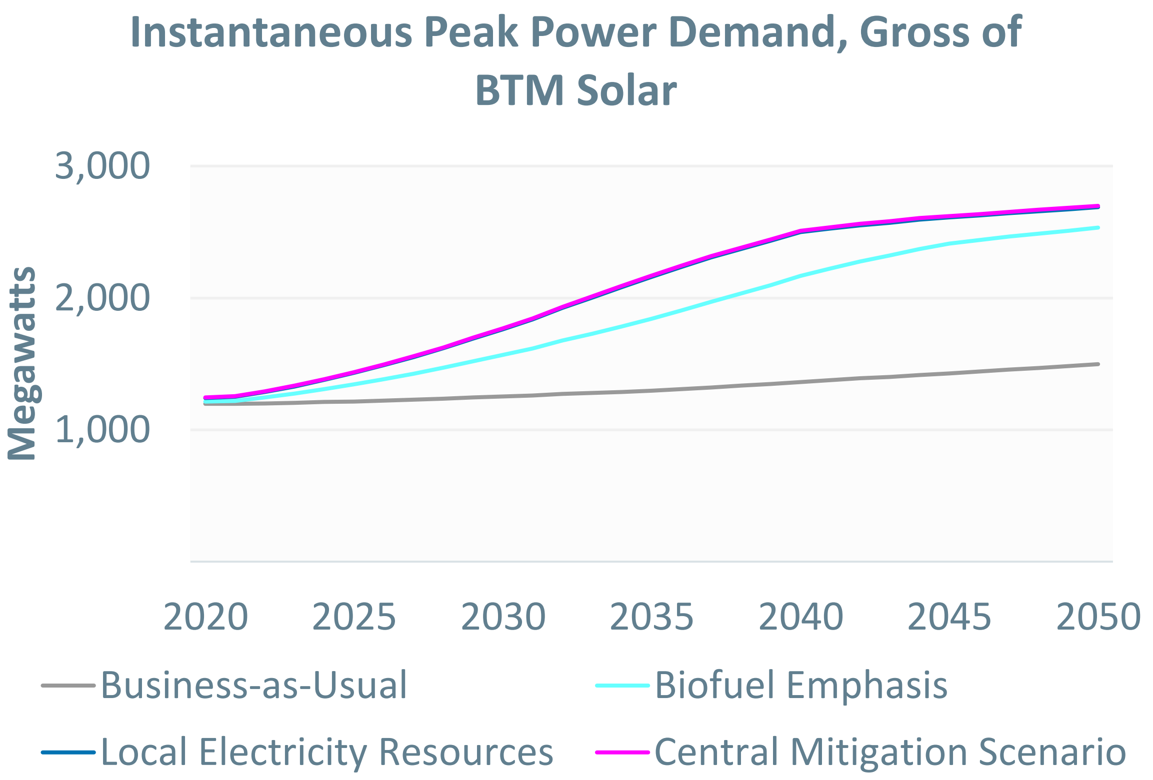
Detail: Sector Contributions to Electric Load



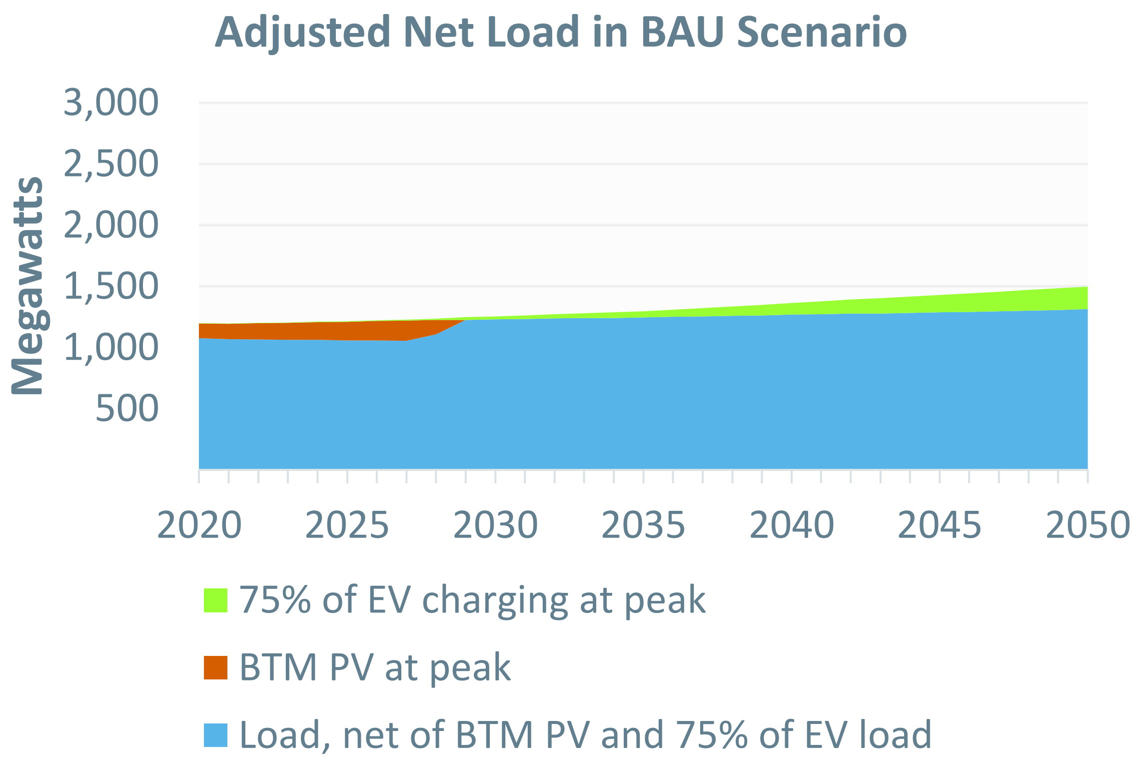


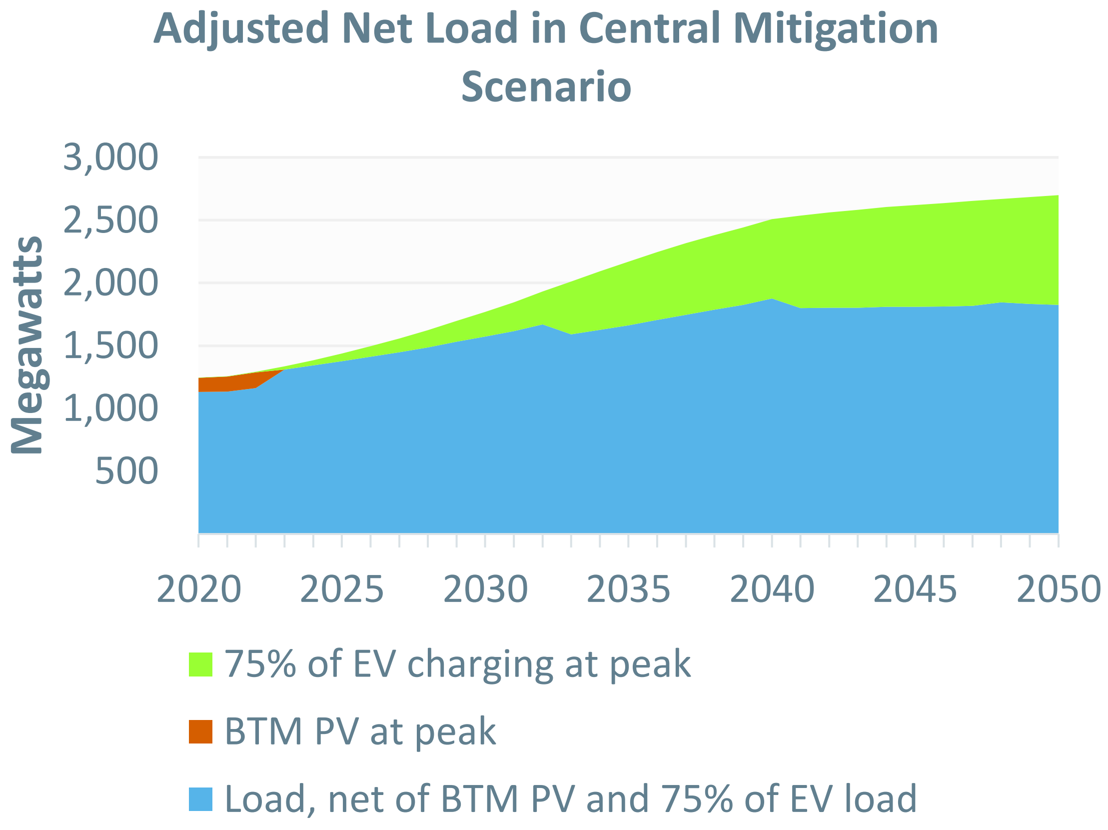
Peak System-Wide Load

- New electric technologies (heat pumps, EVs) with fixed load shapes drive evolution of peak system load:
  - In *magnitude*, and
  - In *timing.*
- Load is met using electricity supply resources, including behind-the-meter (BTM) PV



Detail: Peak System-Wide Load, Adjusted

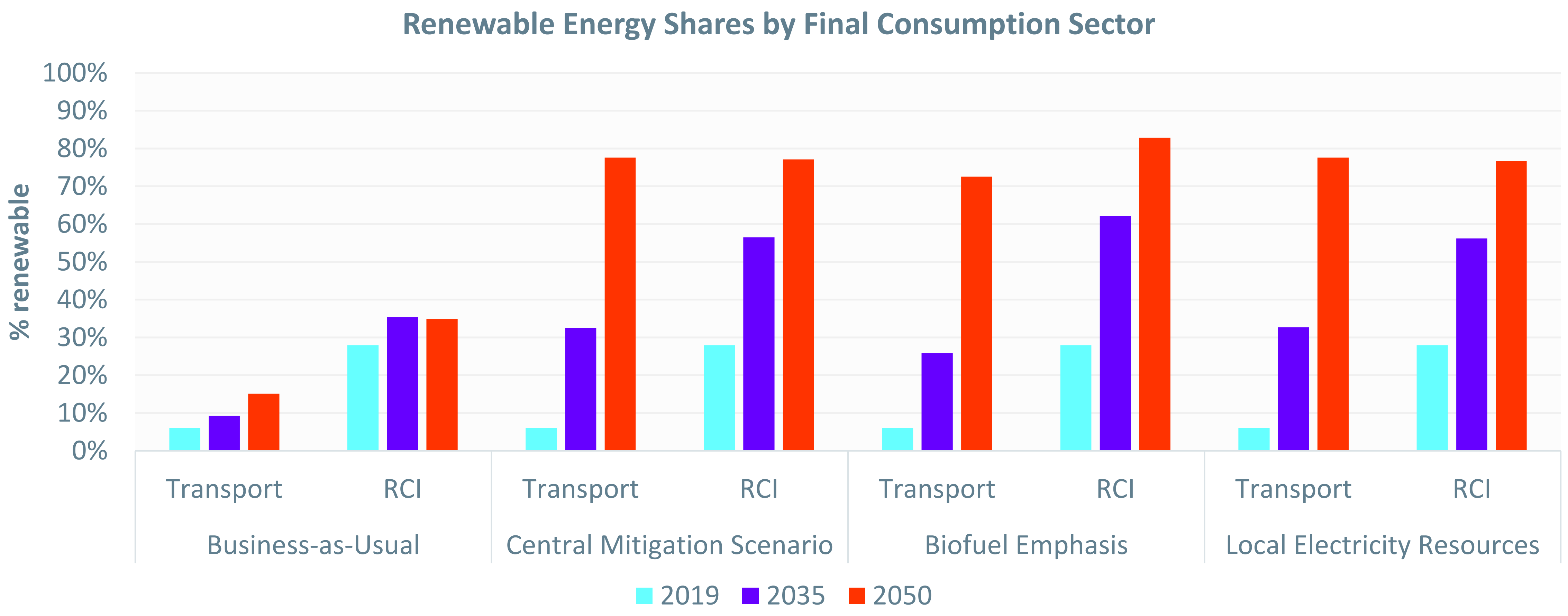




Based on guidance from PSD, adjusted net load removes BTM PV and 75% of EV charging demand at the time that system peak occurs.

Net load is measured forward-of-the-meter, accounting for 8% transmission and distribution loss.

Renewable Energy



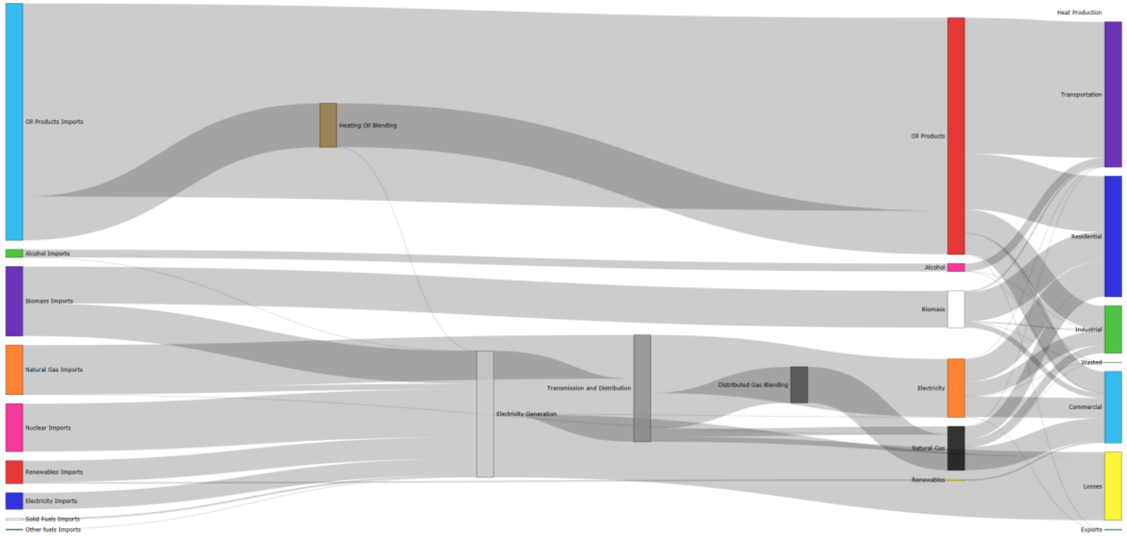
* RCI = Residential, commercial and industrial sectors, combined.

Includes renewable portion (where applicable) of electricity, distributed gas and heating oil.

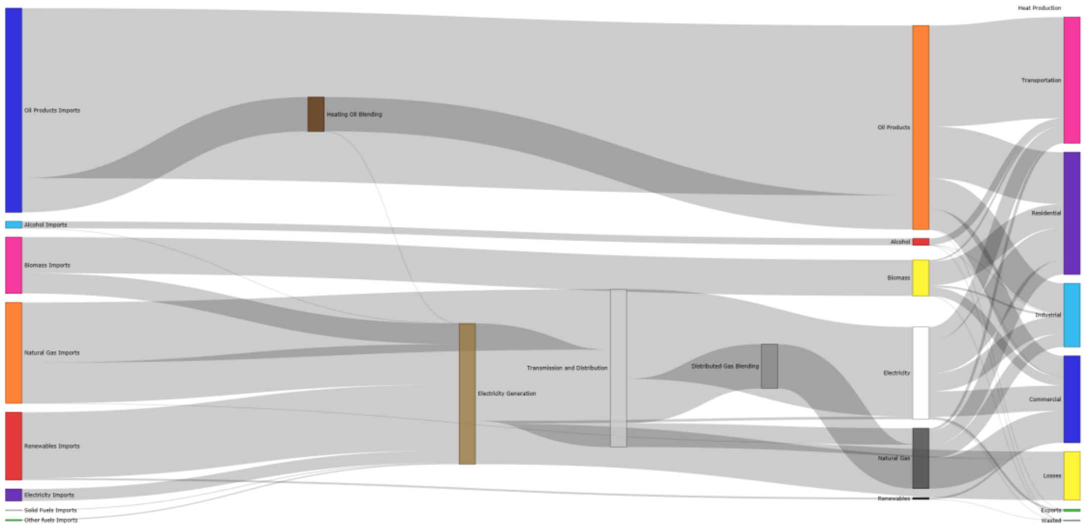
Energy Flow Diagrams

2020 and 2050 (BAU Scenario) Comparison

Energy Flows in 2020



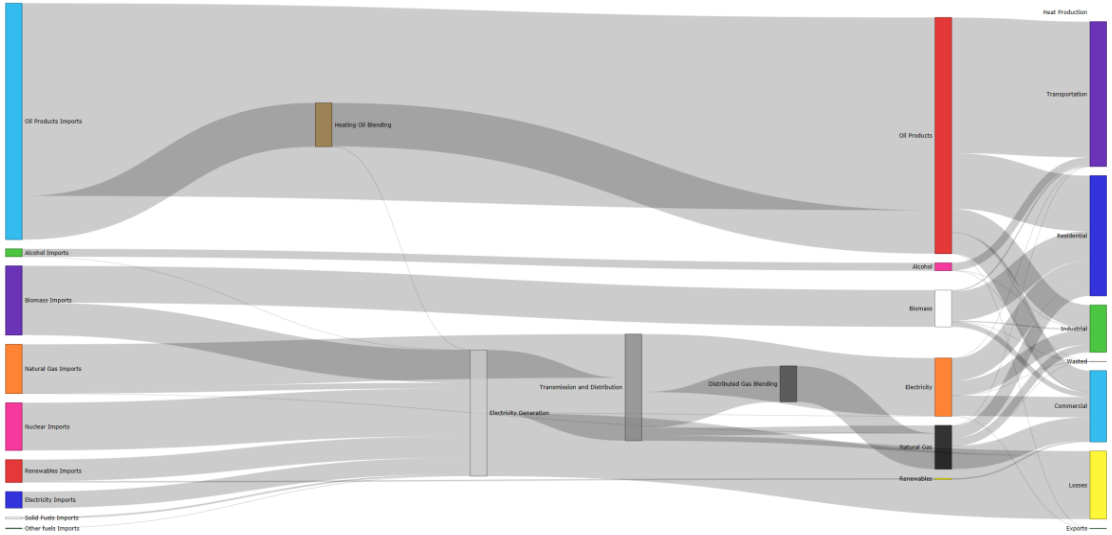
Energy Flows in 2050, BAU



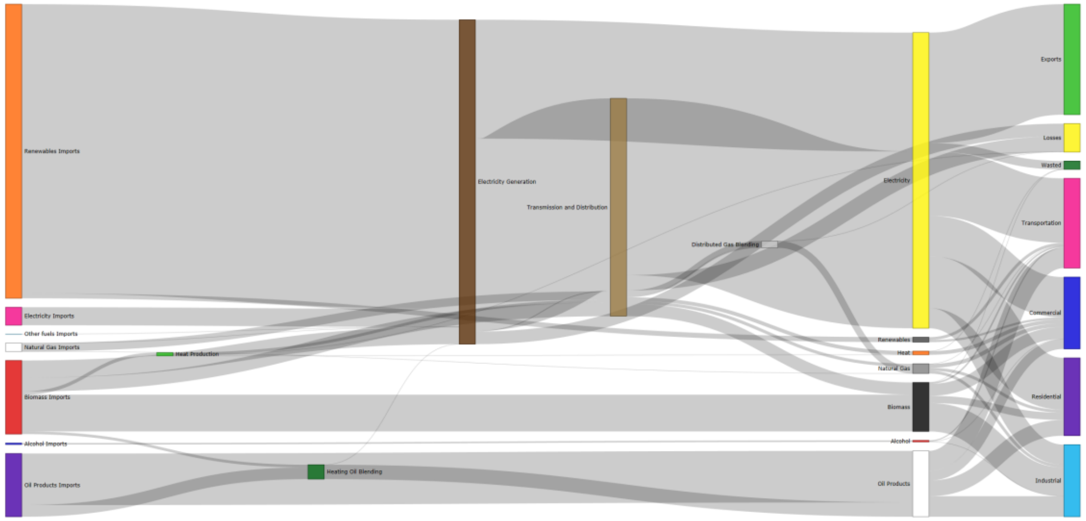
Energy Flow Diagrams

2020 and 2050 (Central Mitigation Scenario) Comparison

Energy Flows in 2020



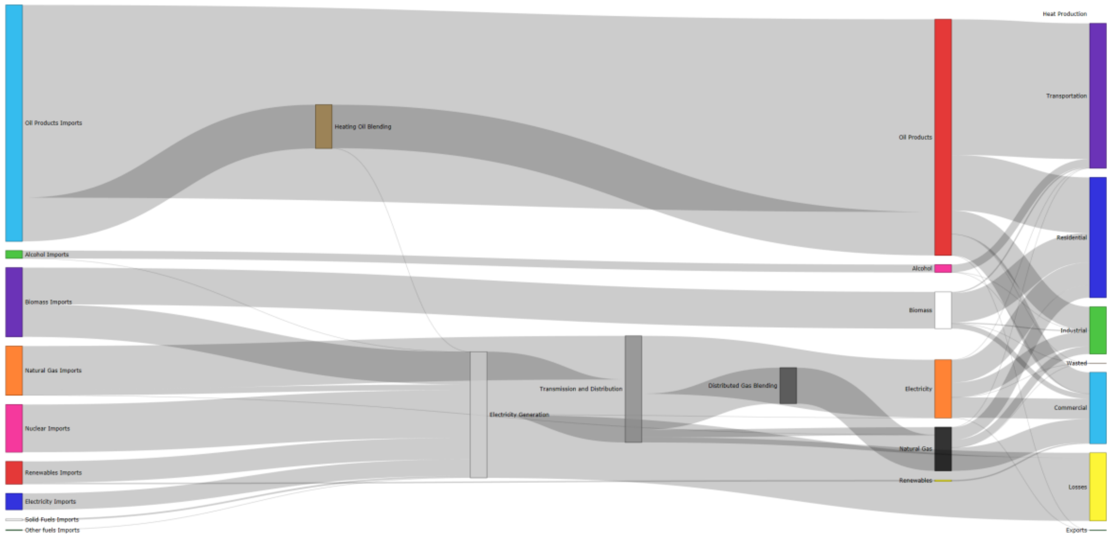
Energy Flows in 2050, Central Mitigation



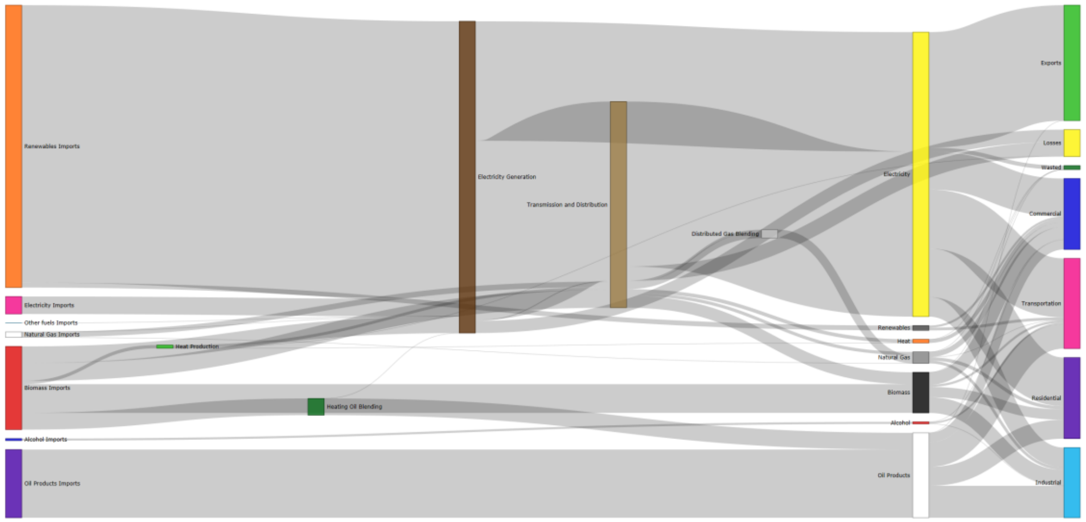
Energy Flow Diagrams

2020 and 2050 (Biofuel Emphasis Scenario) Comparison

Energy Flows in 2020



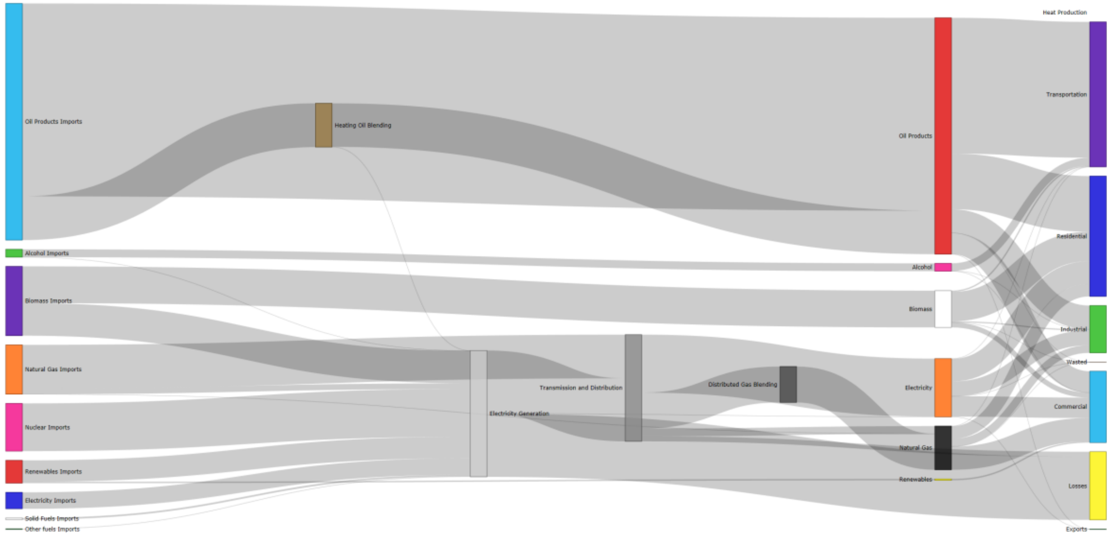
Energy Flows in 2050, Biofuel Emphasis



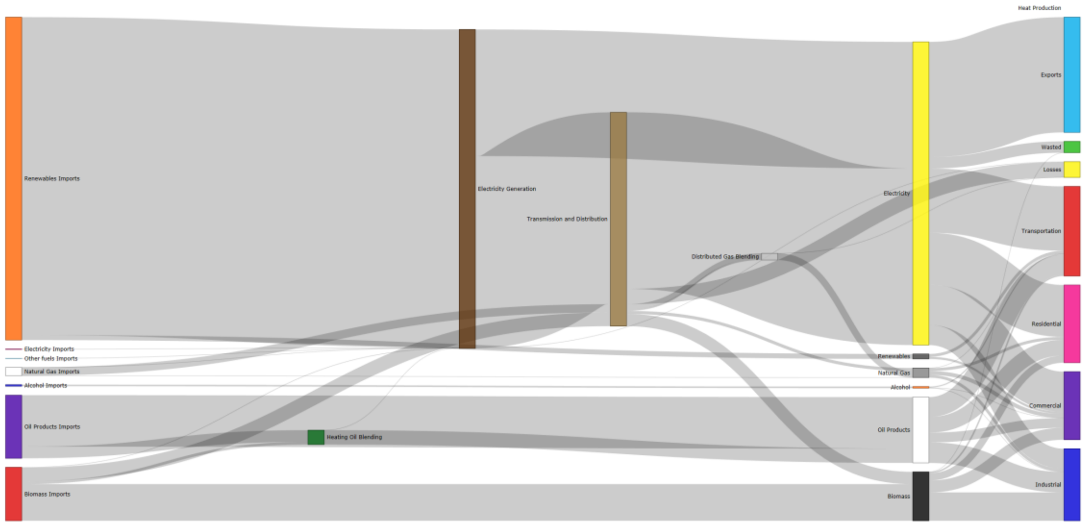
Energy Flow Diagrams

2020 and 2050 (Local Electricity Resources Scenario) Comparison

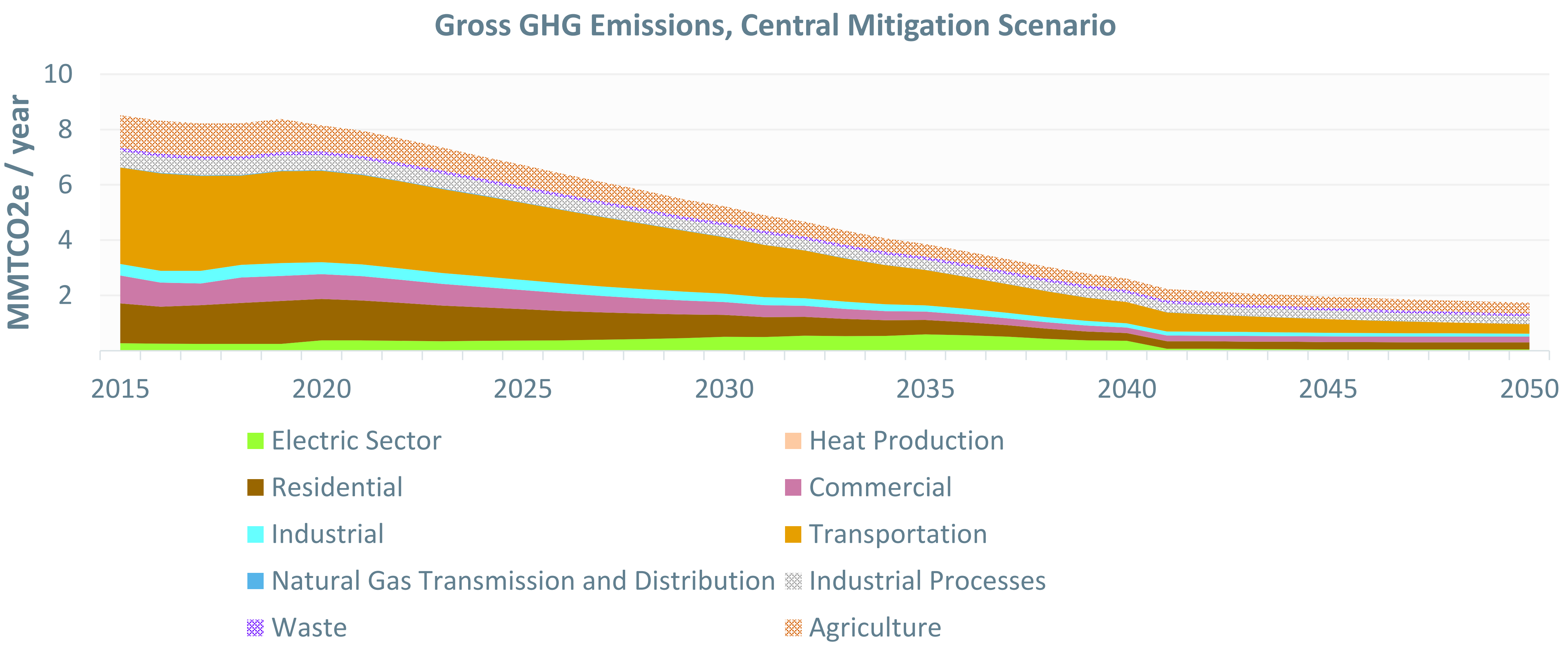
Energy Flows in 2020



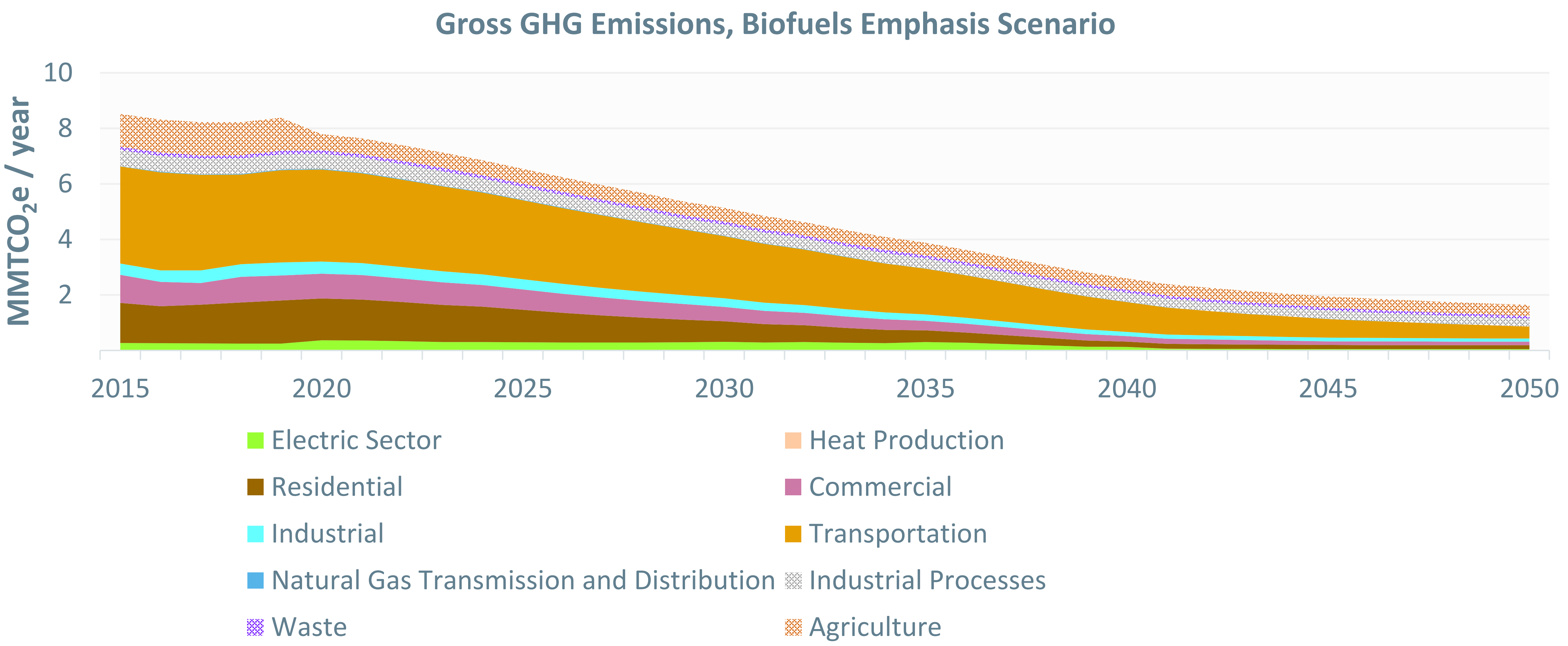
Energy Flows in 2050, Local Electricity



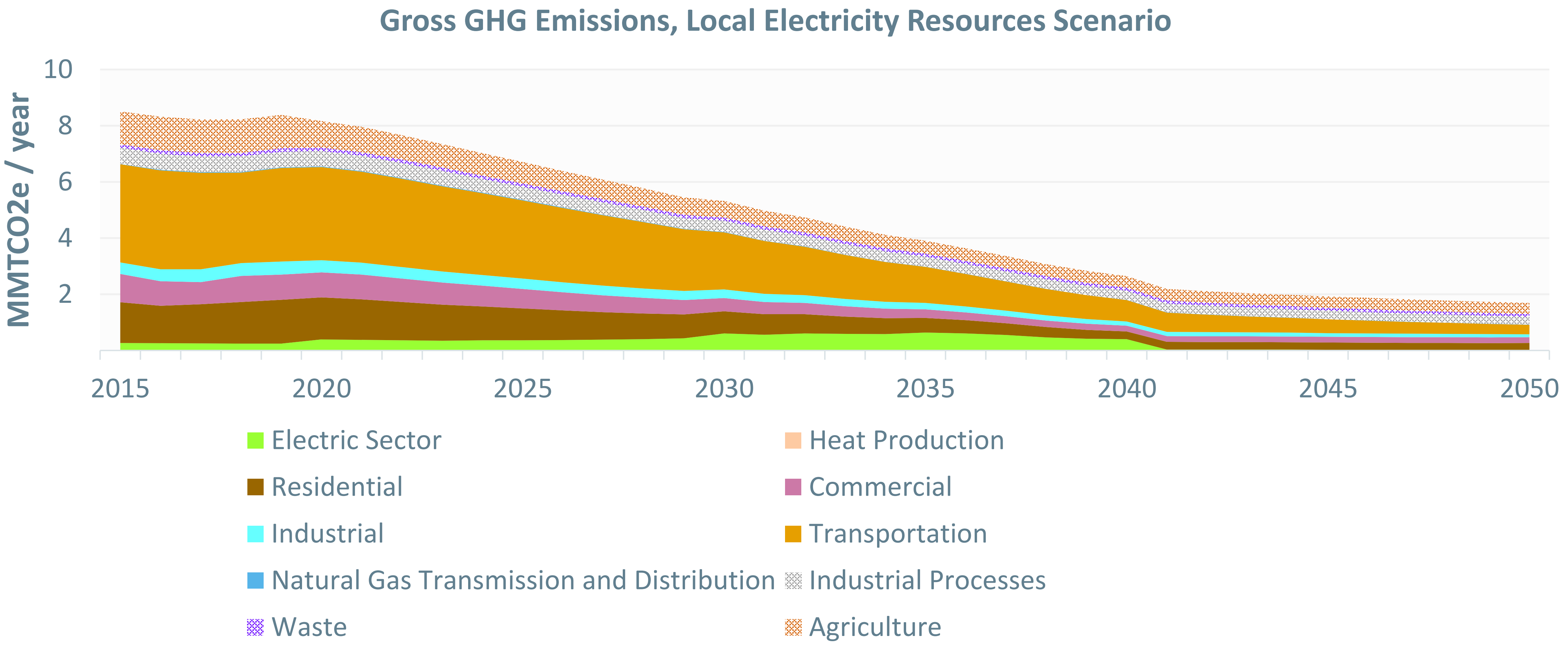
GHG Emissions, Central Mitigation



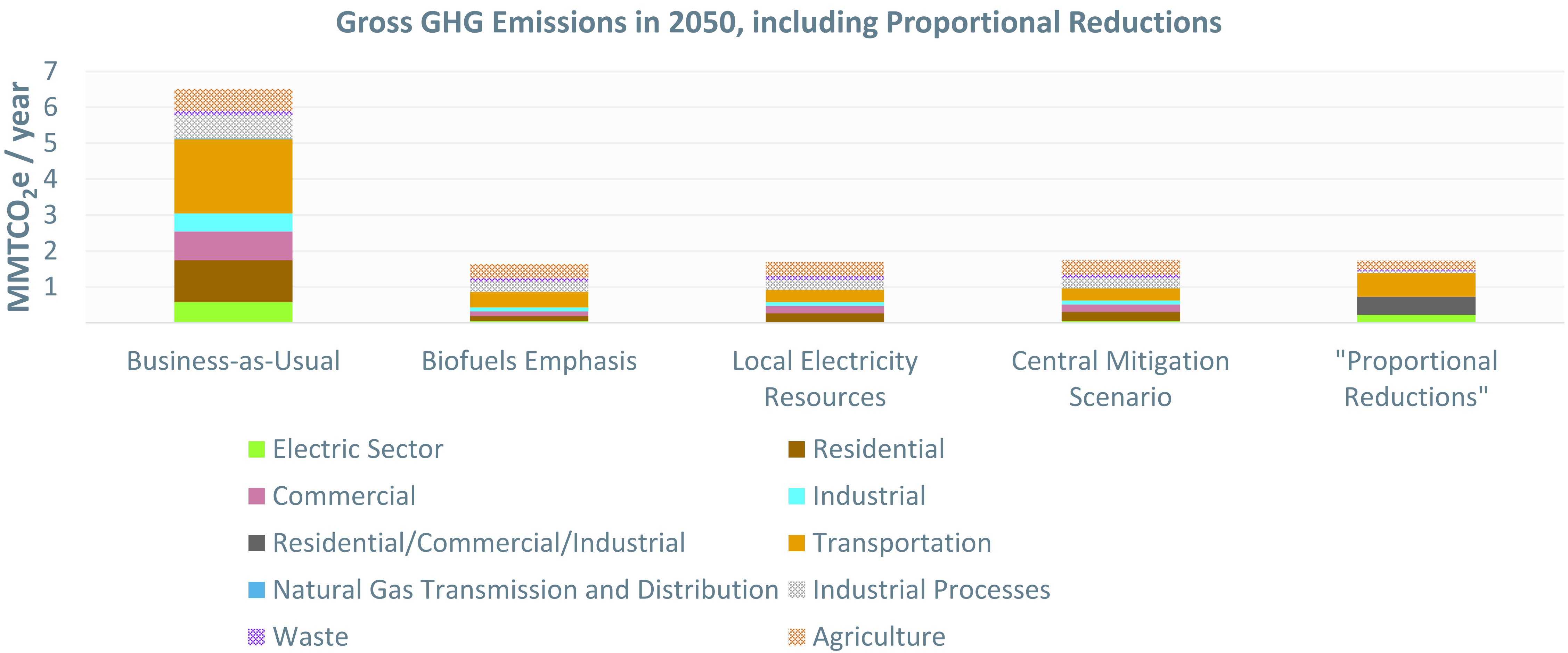
GHG Emissions, Biofuels Emphasis



GHG Emissions, Local Electricity Resources

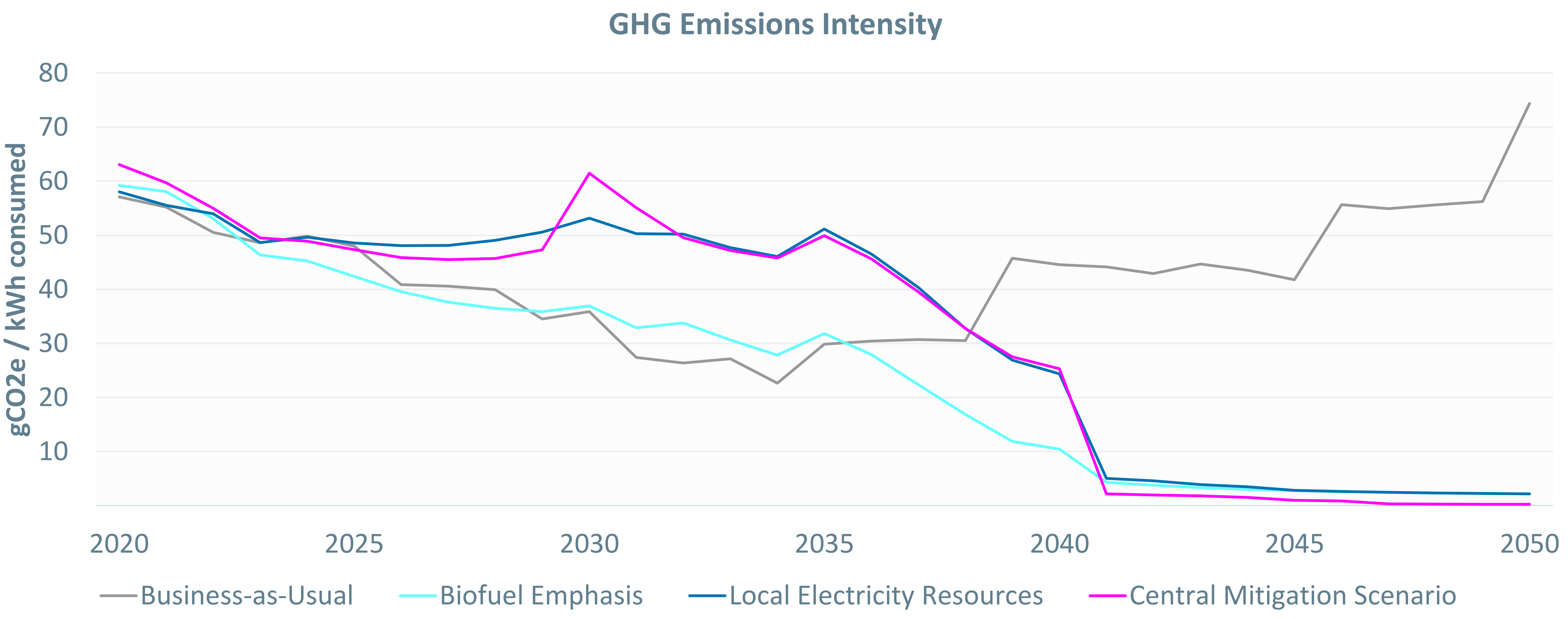


Remaining GHG Emissions in 2050



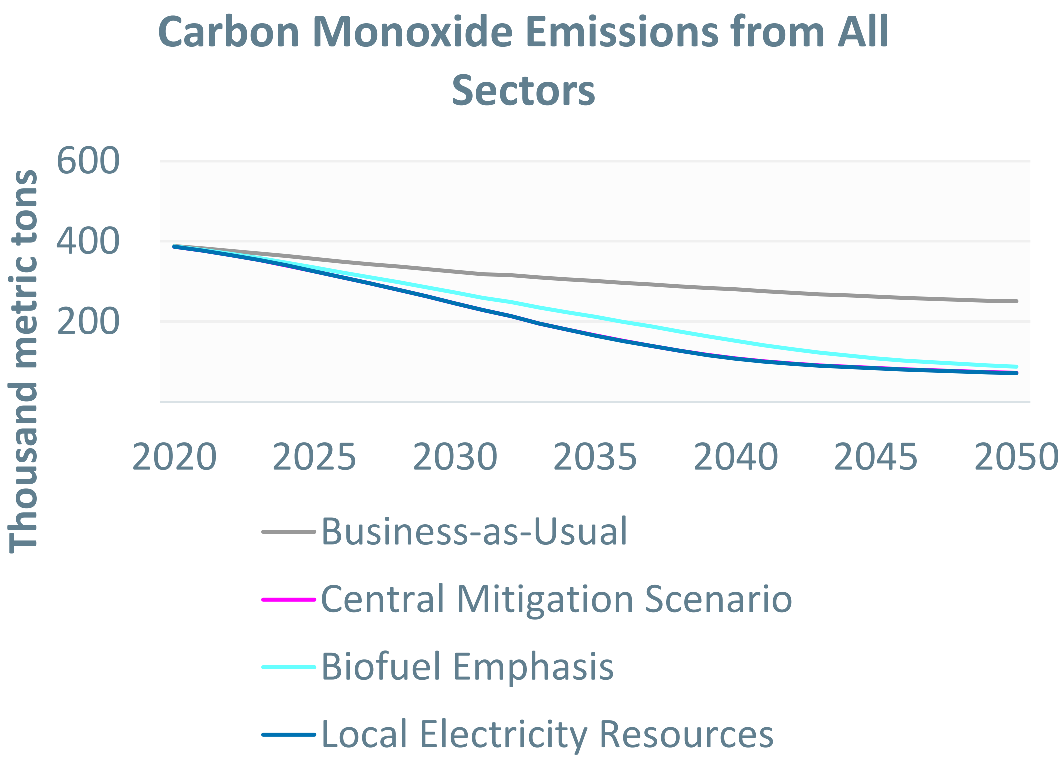
* "Proportional Reductions" shows GWSA targets applied to each sector individually. Proportional emissions for residential, commercial and industrial sectors cannot be disaggregated because they are combined in 1990 GHG inventory.

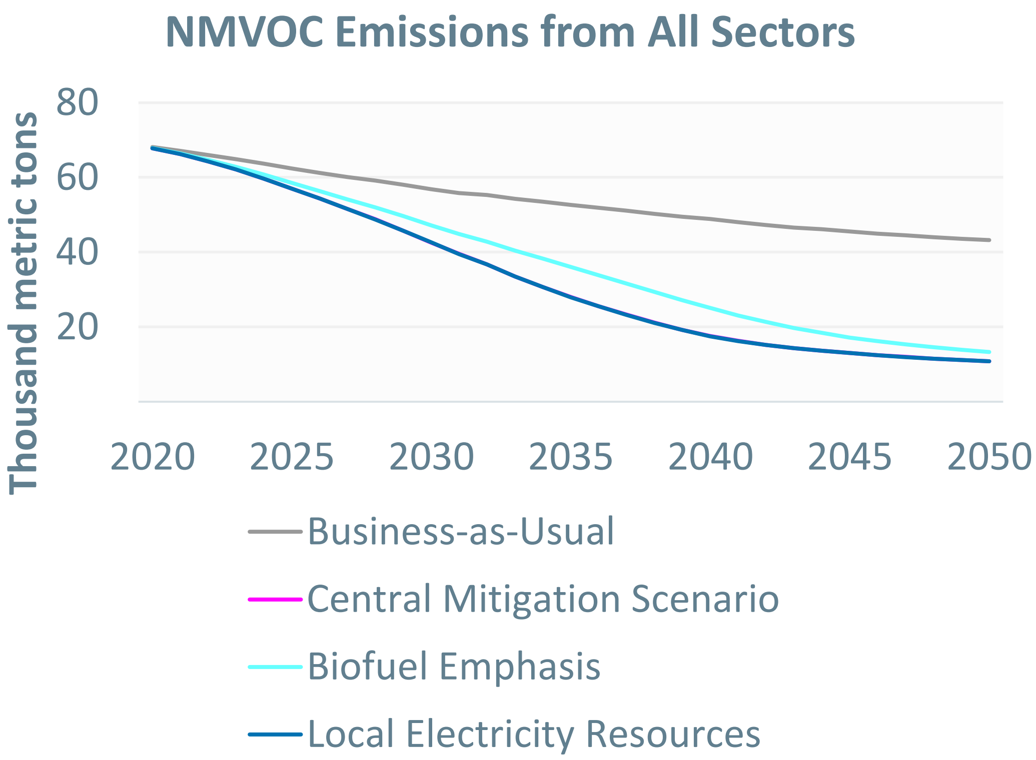
Emissions Intensity of Electricity Consumption



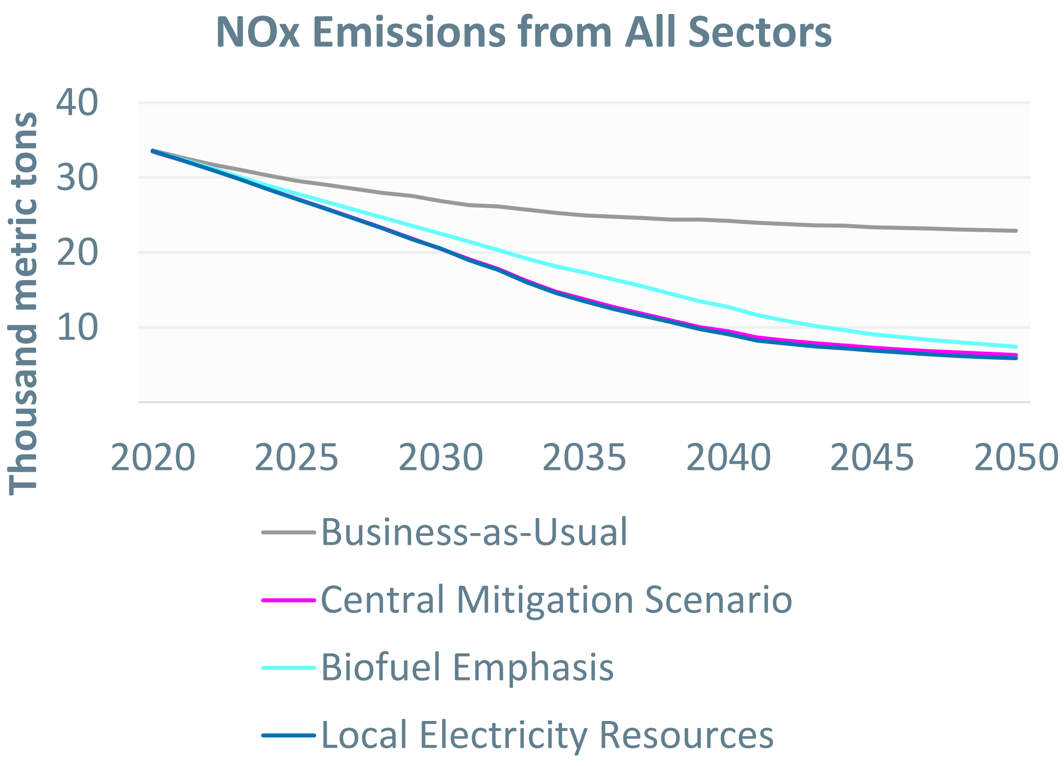
* “Proportional Reductions” shows GWSA targets applied to each sector individually. Proportional emissions for residential, commercial and industrial sectors cannot be disaggregated because they are combined in 1990 GHG inventory.

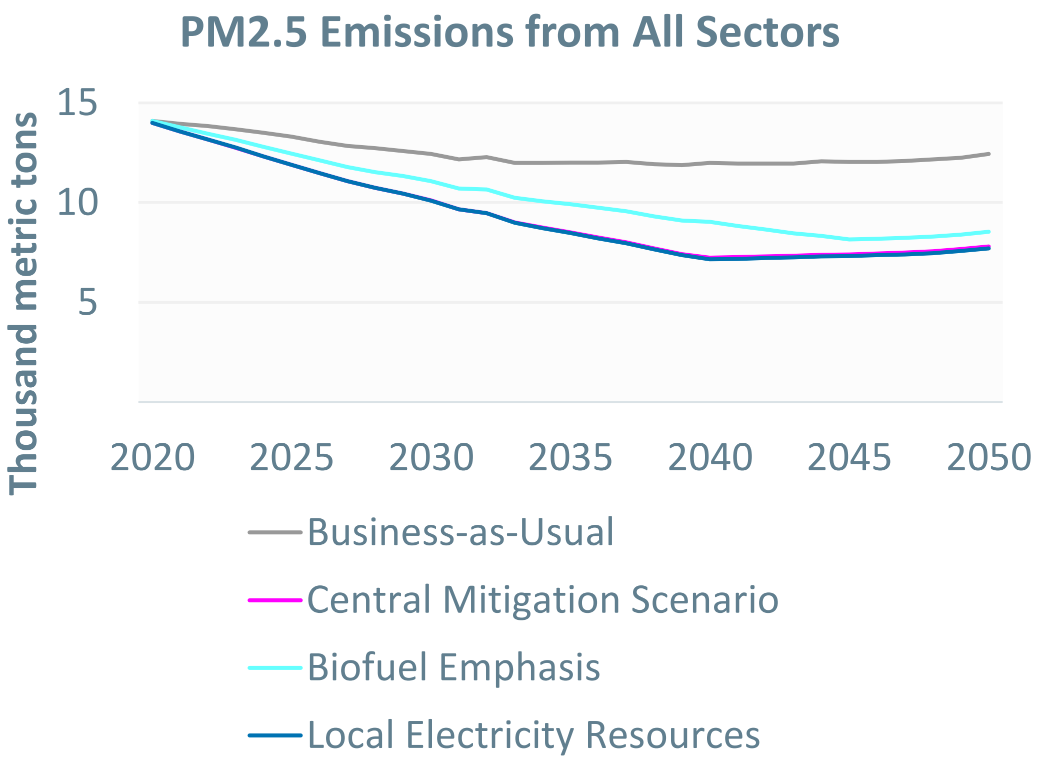
Non-GHG Pollutant Emissions



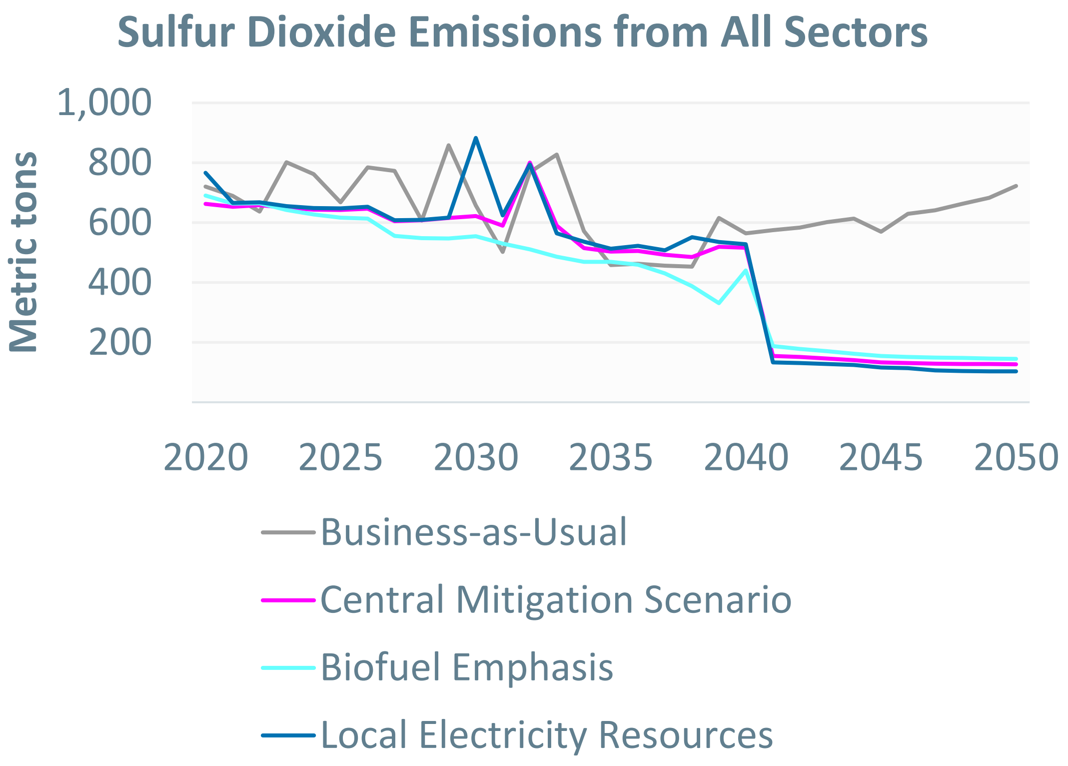


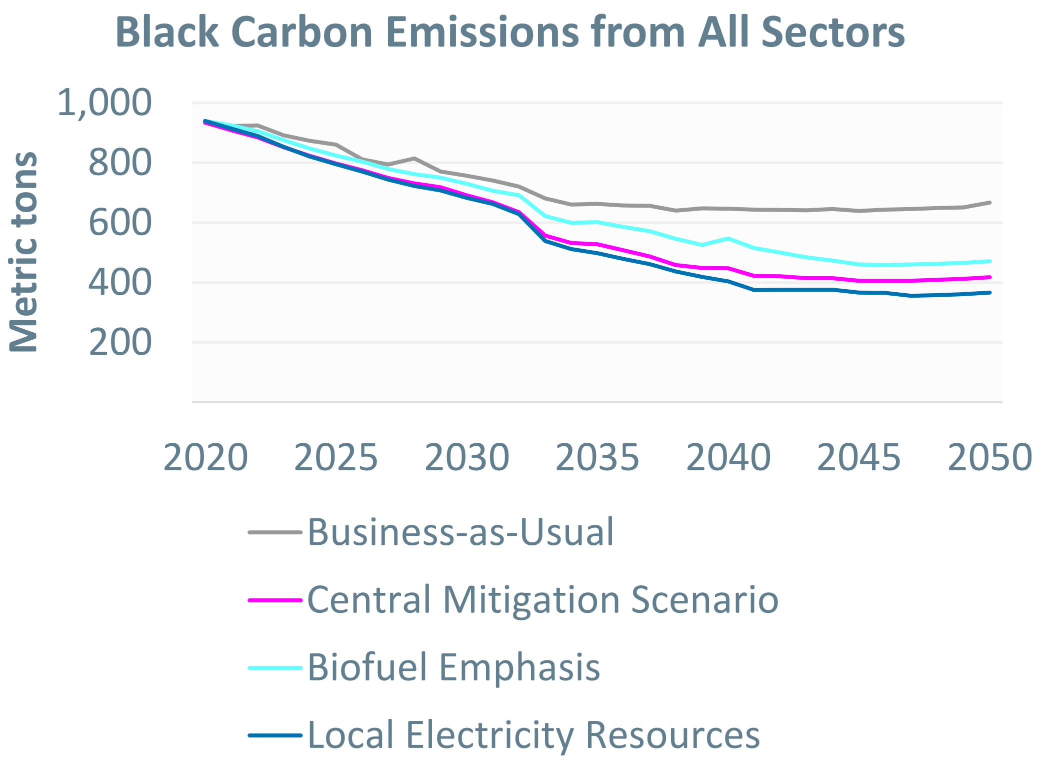
Non-GHG Pollutant Emissions





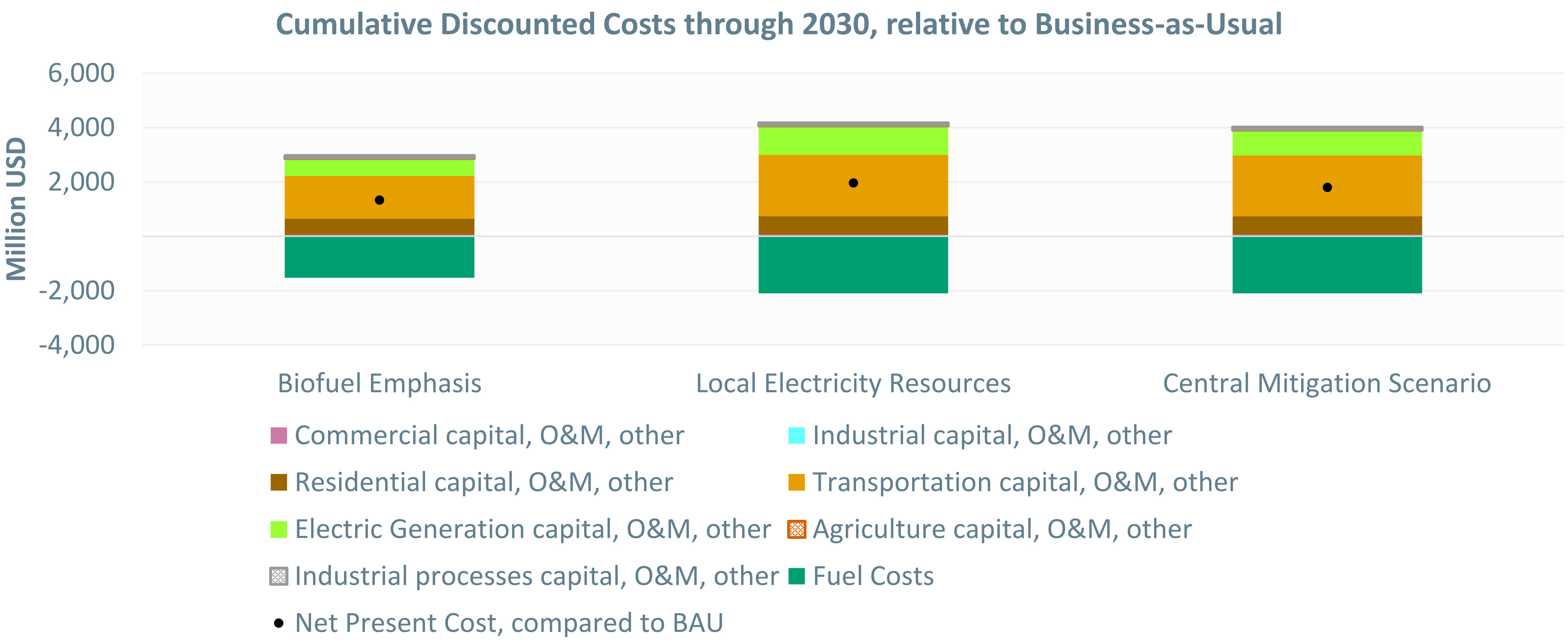
Non-GHG Pollutant Emissions





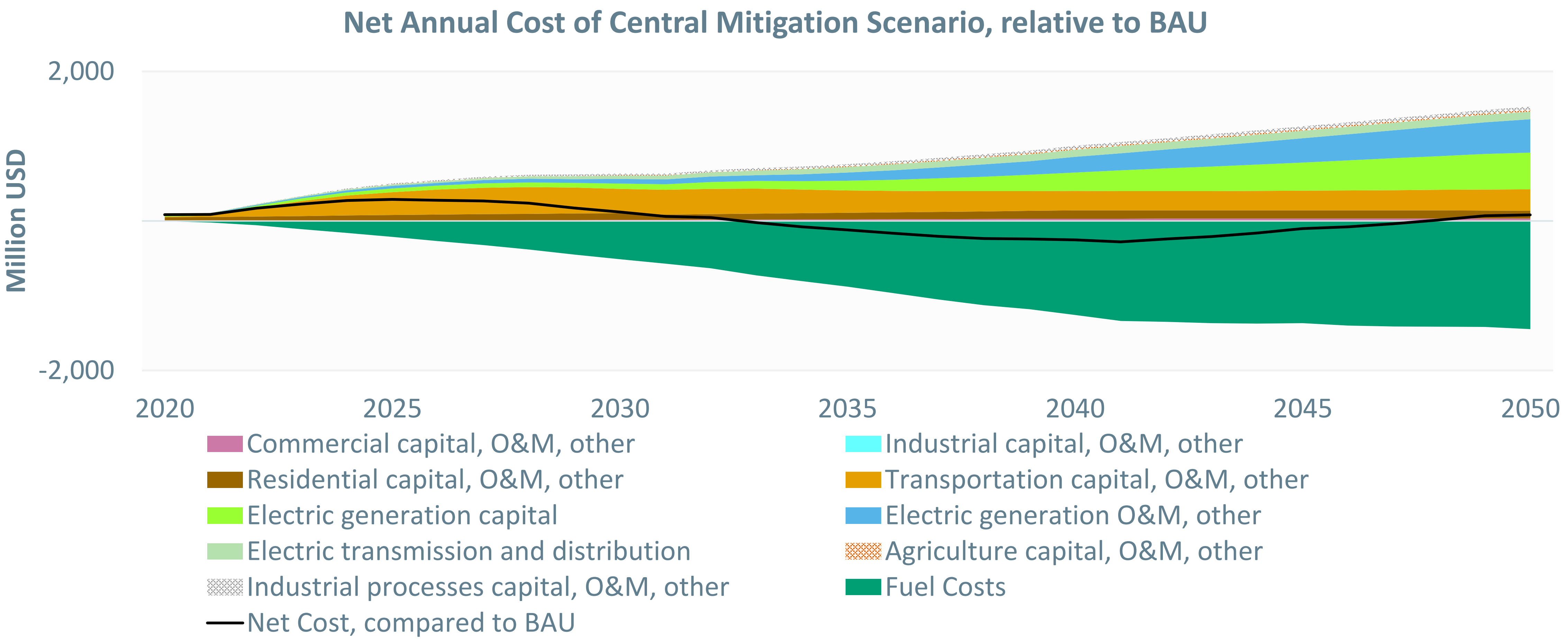
Net Present Value by Scenario

Near Term, to 2030 Only



* Negative values indicate cost savings in a mitigation scenario, relative to BAU. A 2% discount rate is used for NPV calculations. Gross of all federal or state purchase incentives.

Net Mitigation Cost



* Negative values indicate cost savings in the mitigation scenario, relative to BAU. Costs are real 2019 USD. Gross of all federal or state purchase incentives.